3. SUMMARY OF WESTERN NORTH PACIFIC AND NORTH INDIAN OCEAN TROPICAL CYCLONES

3.1 GENERAL

For the western North Pacific, 1991 was another record-breaking year for the number of warnings issued — 835 (41 more than last year) on 32 tropical cyclones (Table 3-1). If Enrique (06E) which tracked westward from the Eastern Pacific is considered, this was one more than the climatological mean of 31 and a carbon copy of 1990 (Table 3-2). The North Indian Ocean was moderately active with four tropical cyclones, which is just below the climatological average of five. The North Indian Ocean Season included the devastating super cyclone 02B. During the year, a record 891 warnings were issued for 36 tropical cyclones in the Northern Hemisphere. A chronology of activity is provided in Figure 3-1.

In the western North Pacific, JTWC was in warning status 169 days during 1991 compared to 165 in 1990 and 154 in 1989. Again only considering the western North Pacific, there were 47 days when the Center issued warnings on two or more tropical cyclones and 18 days when it warned on three (Table 3-3) at a time. There were no days in the Northern Hemisphere when warnings were issued on four or more tropical cyclones at once. When the North Indian Ocean is included in the total, there were 178 days with warnings on one cyclone and 55 days with two. Thirty-seven initial Tropical Cyclone Formation Alerts were issued on western North Pacific tropical disturbances (Table 3-4) and five on disturbances in the North Indian Ocean. Alerts preceded warnings on all significant tropical cyclones in the western North Pacific and North Indian Ocean with the exception of Tropical Depression 15W and Enrique (06E) which regenerated rather rapidly.

TABLE 3-2 **WESTERN NORTH PACIFIC TROPICAL CYCLONE DISTRIBUTION**

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTALS
1959	0	1	1	1	0	1	3	8	9	3	2	2	31
	000	010	010	100	000	001	111	512	423	210	200	200	17 7 7
1960	1	0	1	1	1	3	3	9	5	4	1	1	30
	001	000	001	100	010	210	210	810	041	400	100	100	19 8 3
1961	1	1	1	1	4	6	5	7	6	7	2	1	42
	010	010	100	010	211	114	320	313	510	322	101	100	20 11 11
1962	0	1	0	1	3	0	8	8	7	5	4	2	39
	000	010	000	100	201	000	512	701	313	311	301	020	24 6 9
1963	0	0	1	1	0	4	5	4	4	6	0	3	28
	000	000	001	100	000	310	311	301	220	510	000	210	19 6 3
1964	0	0	0	0	3	2	8	8	8	7	6	2	44
	000	000	000	000	201	200	611	350	521	331	420	101	26 13 5
1965	2	2	1	1	2	4	6	7	9	3	2	1	40
	110	020	010	100	101	310	411	322	531	201	110	010	21 13 6
1966	0	0	0	1	2	1	4	9	10	4	5	2	38
	000	000	000	100	200	100	310	531	532	112	122	101	20 10 8
1967	1	0	2	1	1	1	8	10	8	4	4	1	41
	010	000	110	100	010	100	332	343	530	211	400	010	20 15 6
1968	0	1	0	1	0	4	3	8	4	6	4	0	31
	000	001	000	100	000	202	120	341	400	510	400	000	20 7 4
1969	1	0	1	1	0	0	3	3	6	5	2	1	23
	100	000	010	100	000	000	210	210	204	410	110	010	13 6 4
1970	0	1	0	0	0	2	3	7	4	6	4	0	27
	000	100	000	000	000	110	021	421	220	321	130	000	12 12 3
1971	1	0	1	2	5	2	8	5	7	4	2	0	37
	010	000	010	200	230	200	620	311	511	310	110	000	24 11 2
1972	1	0	1	0	0	4	5	5	6	5	2	3	32
	100	000	001	000	000	220	410	320	411	410	200	210	22 8 2
1973	0	0	0	0	0	0	7	6	3	4	3	0	23
	000	000	000	000	000	000	430	231	201	400	030	000	12 9 2
1974	1	0	1	1	1	4	5	7	5	4	4	2	35
	010	000	010	010	100	121	230	232	320	400	220	020	15 17 3
1975	1	0	0	1	0	0	1	6	5	6	3	2	25
	100	000	000	001	000	000	010	411	410	321	210	002	14 6 5
1976	1	1	0	2	2	2	4	4	5	0	2	2	25
	100	010	000	110	200	200	220	130	410	000	110	020	14 11 0
1977	0	0	1	0	1	1	4	2	5	4	2	1	21
	000	000	010	000	001	010	301	020	230	310	200	100	11 8 2
1978	1	0	0	1	0	3	4	8	4	7	4	0	32
	010	000	000	100	000	030	310	341	310	412	121	000	15 13 4
1979	1	0	1	1	2	0	5	4	6	3	2	3	28
	100	000	100	100	011	000	221	202	330	210	110	111	14 9 5
1980	0	0	1	1	4	1	5	3	7	4	1	1	28
	000	000	001	010	220	010	311	201	511	220	100	010	15 9 4
1981	0	0	1	1	1	2	5	8	4	2	3	2	29
	000	000	100	010	010	200	230	251	400	110	210	200	16 12 1
1982	0	0	3	0	1	3	4	5	6	4	1	1	28
	000	000	210	000	100	120	220	500	321	301	100	100	19 7 2
1983	0	0	0	0	0	1	3	6	3	5	5	2	25
	000	000	000	000	000	010	300	231	111	320	320	020	12 11 2
1984	0	0	0	0	0	2	5	7	4	8	3	1	30
	000	000	000	000	000	020	410	232	130	521	300	100	16 11 3
1985	2	0	0	0	1	3	1	7	5	5	1	2	27
	020	000	000	000	100	201	100	520	320	410	010	110	17 9 1
1986	0	1	0	1	2	2	2	5	2	5	4	3	27
	000	100	000	100	110	110	200	410	200	320	220	210	19 8 0
1987	1	0	0	1	0	2	4	4	7	2	3	1	25
	100	000	000	010	000	110	400	310	511	200	120	100	18 6 1
1988	1	0	0	0	1	3	2	5	8	4	2	1	27
	100	000	000	000	100	111	110	230	260	400	200	010	14 12 1
1989	1	0	0	1	2	2	6	8	4	6	3	2	35
	010	000	000	100	200	110	231	332	220	600	300	101	21 10 4

TABLE CONTINUED ON TOP OF NEXT PAGE

CONTINUED FROM PREVIOUS PAGE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTALS
1990	1	0	0	0	2	4	4	5	5	5	4	1	32
	100	000	000	000	110	211	220	500	410	230	310	100	21 10 1
1991	0	0	2	1	1	1	4	8	6	3	6	0	32
	000	000	110	010	100	100	400	332	420	300	330	000	20 10 2
(1959-1991)													
MEAN:	0.6	0.3	0.6	0.7	1.3	2.1	4.5	6.2	5.7	4.5	2.9	1.4	30.8
CASES:	19	9	20	24	42	70	148	206	187	150	96	46	1017

The criteria used in Table 3-2 are as follows:

1. If a tropical cyclone was first warned on during the last two days of a particular month and continued into the next month for longer than two days, then that system was attributed to the second month.

2. If a tropical cyclone was warned on prior to the last two days of a month, it was attributed to the first month, regardless of how long the system lasted.

3. If a tropical cyclone began on the last day of the month and ended on the first day of the next month, that system was attributed to the first month. However, if a tropical cyclone began on the last day of the month and continued into the next month for only two days, then it was attributed to the second month.

TABLE 3-2 LEGEND

Legend: Total for the month → **6**

Typhoons → **3**

Tropical Storms → **1**

Tropical Depressions → **2**

TABLE 3-1

WESTERN NORTH PACIFIC SIGNIFICANT TROPICAL CYCLONES FOR 1991

TROPICAL CYCLONE		PERIOD OF WARNING	NUMBER OF WARNINGS ISSUED	MAXIMUM SURFACE WINDS KT (M/SEC)	ESTIMATED MSLP (MB)
(01W)	TS SHARON	05 MAR - 14 MAR	33	60 (31)	980
(02W)	TY TIM	21 MAR - 25 MAR	20	70 (36)	972
(03W)	TS VANESSA	23 APR - 28 APR	20	45 (23)	991
(04W)	STY WALT	06 MAY - 16 MAY	40	140 (72)	898
(05W)	TY YUNYA	13 JUN - 17 JUN	16	105 (54)	938
(06W)	TY ZEKE	09 JUL - 14 JUL	21	80 (41)	963
(07W)	TY AMY	15 JUL - 20 JUL	18	125 (64)	916
(08W)	TY BRENDAN	21 JUL - 24 JUL	16	70 (36)	972
(09W)	TY CAITLIN	23 JUL - 30 JUL	27	95 (49)	949
(06E)	TS ENRIQUE	01 AUG - 01 AUG	3	35 (18)	997
(10W)	TS DOUG	08 AUG - 11 AUG	9	35 (18)	997
(11W)	TY ELLIE	10 AUG - 19 AUG	34	85 (44)	958
(12W)	TY FRED	11 AUG - 18 AUG	27	95 (49)	949
(13W)	TD 13W	12 AUG - 13 AUG	5	25 (13)	1004
(14W)	TY GLADYS	16 AUG - 23 AUG	31	65 (33)	973
(15W)	TD 15W	26 AUG - 29 AUG	11	30 (15)	997
(16W)	TS HARRY	29 AUG - 31 AUG	10	40 (21)	994
(17W)	TY IVY	02 SEP - 10 SEP	32	115 (59)	927
(18W)	TS JOEL	03 SEP - 07 SEP	15	55 (28)	982
(19W)	TY KINNA	10 SEP - 14 SEP	17	90 (46)	954
(20W)	TS LUKE	14 SEP - 19 SEP	20	50 (26)	987
(21W)	STY MIREILLE	16 SEP - 27 SEP	48	130 (67)	910
(22W)	TY NAT	16 SEP - 02 OCT	61	110 (57)	933
(23W)	TY ORCHID	04 OCT - 13 OCT	37	115 (59)	927
(24W)	TY PAT	05 OCT - 13 OCT	31	125 (64)	916
(25W)	STY RUTH	20 OCT - 31 OCT	40	145 (75)	892
(26W)	STY SETH	01 NOV - 14 NOV	56	130 (67)	910
(27W)	TS THELMA	01 NOV - 08 NOV	23	45 (23)	991
(28W)	TS VERNE	05 NOV - 12 NOV	28	55 (28)	984
(29W)	TS WILDA	14 NOV - 20 NOV	22	45 (23)	991
(30W)	STY YURI	23 NOV - 01 DEC	36	150 (77)	885
(31W)	TY ZELDA	27 NOV - 04 DEC	28	80 (41)	963
		TOTAL:	835		

Figure 3-1. Chronology of western North Pacific and North Indian Ocean tropical cyclones for 1991.

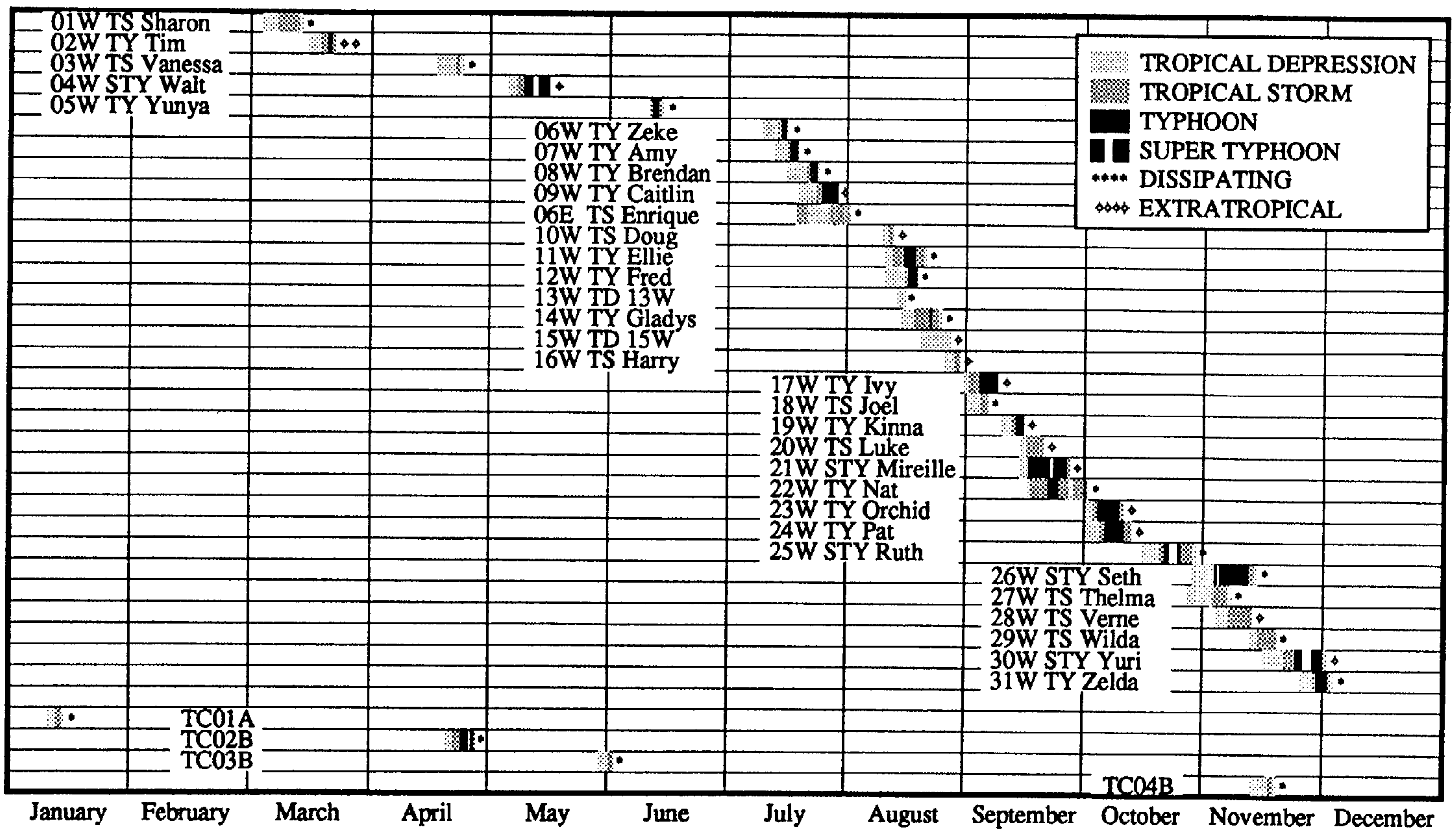


TABLE 3-3

WESTERN NORTH PACIFIC TROPICAL CYCLONES

TYPHOONS

(1945 - 1959)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTALS
MEAN:	0.3	0.1	0.3	0.4	0.7	1.0	2.9	3.1	3.3	2.4	2.0	0.9	16.4
CASES:	5	1	4	6	10	15	29	46	49	36	30	14	245

(1960 - 1991)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTALS
MEAN:	0.3	0.1	0.2	0.5	0.7	1.1	2.7	3.2	3.2	3.1	1.8	0.6	17.5
CASES:	9	2	7	15	24	35	88	102	104	100	57	20	563

TROPICAL STORMS AND TYPHOONS

(1945 - 1959)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTALS
MEAN:	0.4	0.1	0.5	0.5	0.8	1.6	2.9	4.0	4.2	3.3	2.7	1.2	22.2
CASES:	6	2	7	8	11	22	44	60	64	49	41	18	332

(1960 - 1991)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTALS
MEAN:	0.6	0.3	0.5	0.7	1.1	1.8	4.2	5.3	5.0	4.2	2.7	1.2	27.3
CASES:	18	8	15	22	36	59	133	171	159	133	88	38	880

NUMBER OF CALENDAR WARNING DAYS: 169

NUMBER OF CALENDAR WARNING DAYS WITH TWO TROPICAL CYCLONES: 47

NUMBER OF CALENDAR WARNING DAYS WITH THREE TROPICAL CYCLONES:18

TABLE 3-4

TROPICAL CYCLONE FORMATION ALERTS
WESTERN NORTH PACIFIC OCEAN

YEAR	INITIAL TCFAS	TROPICAL CYCLONES WITH TCFAS	TOTAL TROPICAL CYCLONES	FALSE ALARM RATE	PROBABILITY OF DETECTION
1976	34	25	25	26%	100%
1977	26	20	21	23%	95%
1978	32	27	32	16%	84%
1979	27	23	28	15%	82%
1980	37	28	28	24%	100%
1981	29	28	29	3%	96%
1982	36	26	28	28%	93%
1983	31	25	25	19%	100%
1984	37	30	30	19%	100%
1985	39	26	27	33%	96%
1986	38	27	27	29%	100%
1987	31	24	25	23%	96%
1988	33	26	27	21%	96%
1989	51	32	35	37%	91%
1990	33	30	31	9%	97%
1991	37	29	31*	22%	94%
(1976-1991)					
MEAN:	34.4	26.6	28.1	23%	95%
TOTALS:	551	426	449		

1991 FORMATION ALERTS: 30 OF 32 INITIAL FORMATION ALERTS DEVELOPED INTO SIGNIFICANT TROPICAL CYCLONES.

* ENRIQUE(06E) NOT INCLUDED

3.2 WESTERN NORTH PACIFIC TROPICAL CYCLONES

The 12 months of 1991 included five super typhoons, 15 lesser typhoons, 10 tropical storms and two tropical depressions. Again, like the preceding 2 years, this was above average for the number of typhoons and super typhoons, but below average for tropical depressions. A possible record number of five midget tropical cyclones occurred during the year. All tropical cyclones originated in the monsoon trough, near-equatorial trough, or within a Northward-displaced Self-sustaining, Solitary (NSS) monsoon gyre* (Lander, 1992) which dominated the circulation of the western North Pacific during August. None were TUTT-induced, even though the TUTT was much in evidence during the summer.

January and February were months with a very active Australian monsoon and higher than normal surface pressures in the western North Pacific. This pattern changed dramatically in March as pressures rose across northern Australia with the demise of the monsoon. Coincident with the Southern Oscillation Index for March going negative, brisk equatorial westerlies appeared east of New Guinea and cyclonic vortices (including Sharon (01W) and Tim (02W)) formed both north and south of the equator in the twin near-equatorial troughs. These anomalously strong westerly winds continued into April and May, and supported the formation of Vanessa (03W) and Walt (04W) as well. In early May, a strong west-wind burst along the equator led to the formation of Walt (04W) and a southern twin (Lisa (21P)). In June and July, a single monsoon trough became established in the western North Pacific and a near-equatorial buffer zone appeared, as the southern hemisphere near-equatorial trough was replaced by southeasterly flow. With the exception of Enrique (06E), which came westward across the international date line, tropical cyclones Yunya (05W) through Caitlin (09W) developed in this northern hemisphere trough.

After 31 July, when Caitlin dissipated, almost 2 weeks followed without tropical cyclone activity as a major synoptic pattern change occurred in the western North Pacific - a NSS monsoon gyre replaced the normal monsoon trough. In August (Figure 3-2), with the exception of Fred (12W), which developed just east of the central Philippine Islands in an extension of the Asian monsoon trough , Doug (10W) through Harry (16W) formed in the NSS monsoon gyre.

In September (Figure 3-3), after the demise of Harry (16W) and the NSS monsoon gyre, there was another major synoptic pattern change - the monsoon trough reappeared in low latitudes. This trough spawned Ivy (17W) and the remaining tropical cyclones of the year. Starting in October (Figure 3-4), with a moderate El Niño taking shape in the Central Pacific, persistent convection and strong equatorial westerlies became established east of New Guinea. By November, most of the deep convective clouds had moved back along the equator and the twin near-equatorial troughs were established again with named cyclones forming both north and south of the equator.

*Monsoon gyres are modes of the monsoon circulation which are characterized by:
1) a large (diameter on the order of 1000 nm (2000 km)) nearly circular low-level cyclonic vortex;
2) nearly circular isobars with the outermost closed isobar possessing a diameter of roughly 1000 nm (2000 km);
3) a northward displacement of the sea-level pressure minimum with respect to the latitude of the pressure minimum found along any meridian passing through the long-term monthly mean monsoon trough; and
4) lower than average sea-level pressure throughout most of the tropical western North Pacific.

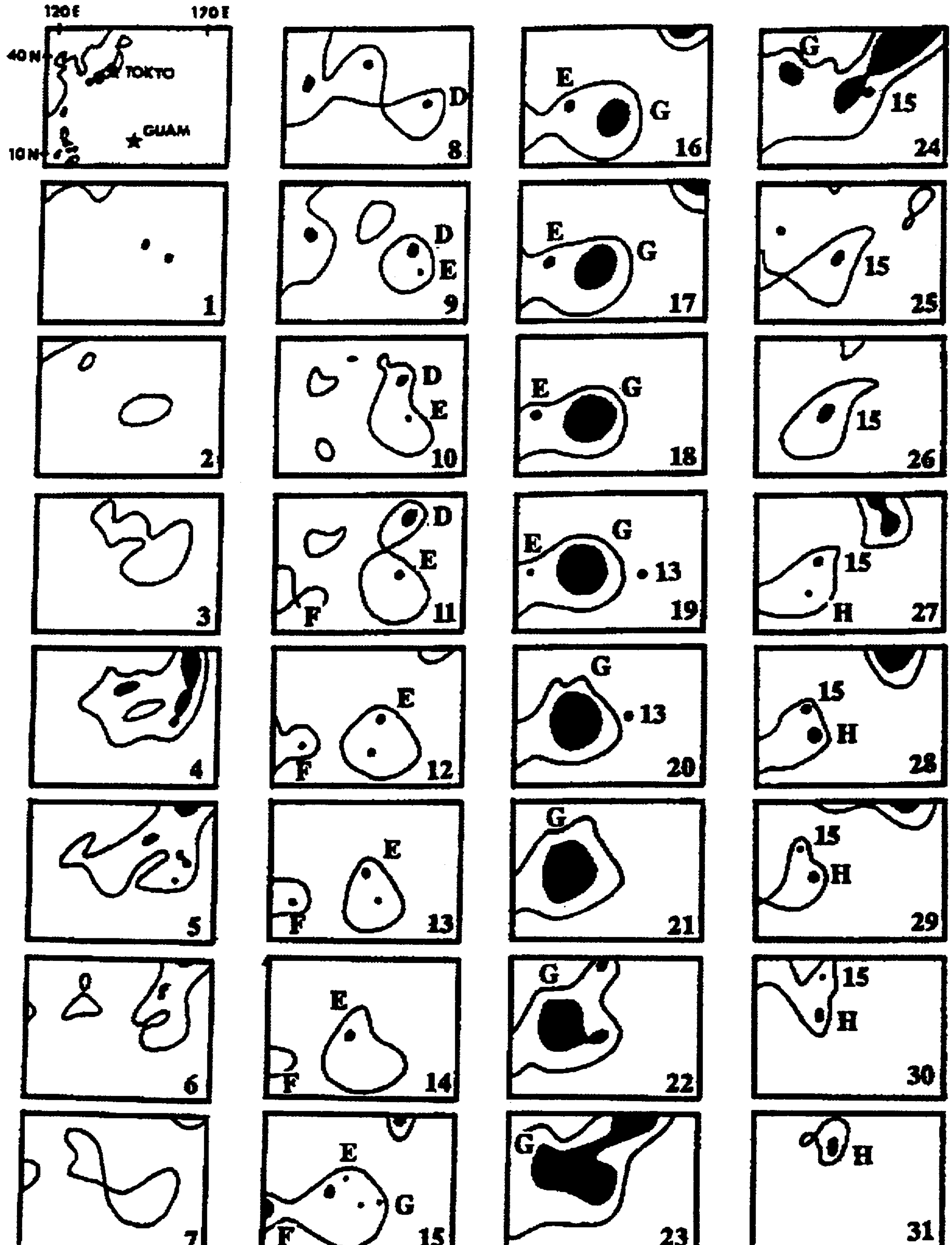


Figure 3-2. Western North Pacific sea-level pressure for August 1991. Outer contour is 1006 mb; black-shaded regions: < 1000 mb. Maps are at 00Z for the date indicated in the lower right of each panel. Geography key appears in upper left panel. Tropical cyclones are indicated: D-Doug (10W), E-Ellie (11W), F-Fred (12W), 13-Tropical Depression 13W, G-Gladys (14W), 15-Tropical Depression 15W and H-Harry (16W). (Adapted from Lander, 1992.)

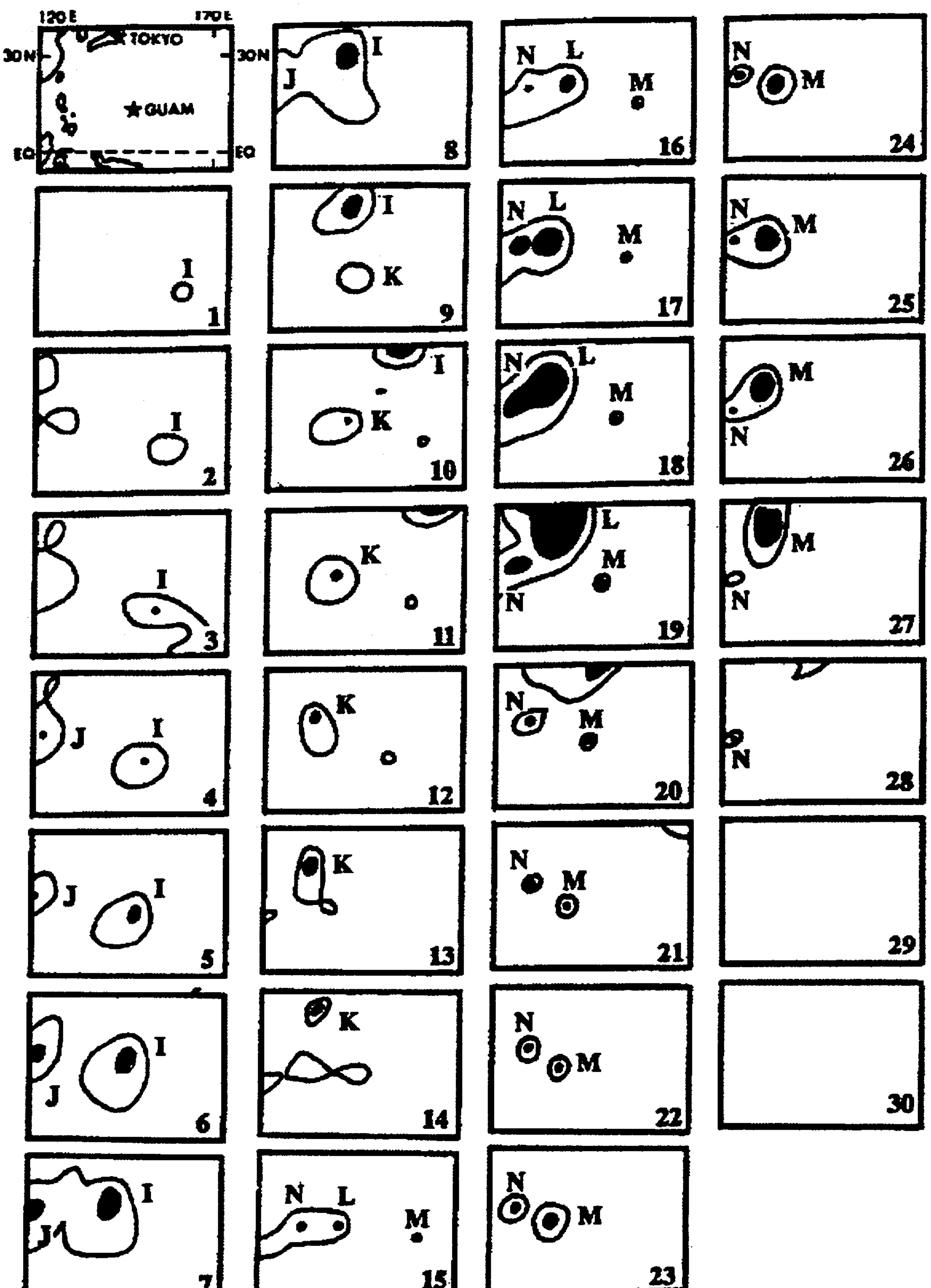


Figure 3-3. Western North Pacific sea-level pressure for September 1991. Outer contour is 1008 mb; black-shaded regions: < 1002 mb. Maps are at 00Z for the date indicated in the lower right of each panel. Geography key appears in upper left panel. Tropical cyclones are indicated: I-Ivy (17W), J-Joel (18W), K-Kinna (19W), L-Luke (20W), M-Mireille (21W) and N-Nat (22W). (Adapted from Lander, 1992.)

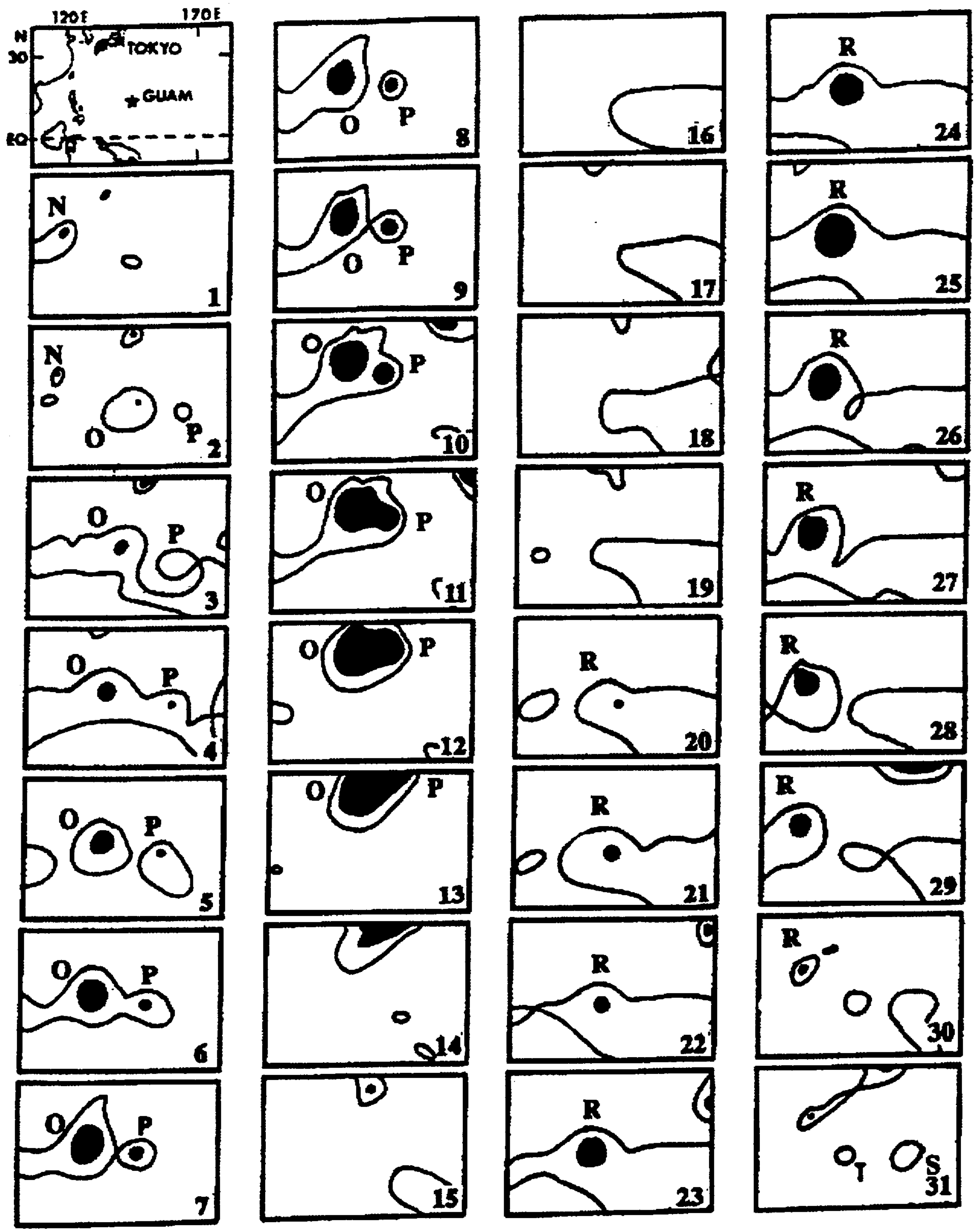


Figure 3-4. Western North Pacific sea-level pressure for October 1991. Outer contour is 1010 mb; black-shaded regions: < 1004 mb. Maps are at 00Z for the date indicated in the lower right of each panel. Geography key appears in upper left panel. Tropical cyclones are indicated: N-Nat (22W), O-Orchid (23W), P-Pat (24W), R-Ruth (25W), S-Seth (26W) and T-Thelma (27W). (Adapted from Lander, 1992.)

JANUARY THROUGH JUNE

The first tropical cyclone of 1991 in the western North Pacific, **Sharon (01W)**, developed the first week of March in conjunction with a burst of equatorial westerly winds that extended eastward from New Guinea to the international date line. Sharon tracked over the central Philippine Islands and continued westward across the South China Sea to dissipate in southeastern Vietnam on 16 March. Close behind Sharon, **Tim (02W)** was the second tropical cyclone to develop in the eastern Caroline Islands during the month of March. The recurvature track taken by Tim proved difficult to predict for JTWC forecasters, because the primary prognostic guidance was slow to depict the changing synoptic situation. Average forecast errors for Tim were the largest of any Northwest Pacific tropical cyclone forecasts in 1991. After Typhoon Tim in mid-March, the near-equatorial trough remained relatively inactive until **Vanessa's (03W)** convection flared up to the south of Guam over a month later. Vanessa moved across the central Philippine Islands as a weak tropical depression, peaked at 45 kt (23 m/sec) in the South China Sea, then the remnants of the tropical storm moved northward through the axis of the subtropical ridge and dissipated southwest of Hong Kong. A week later, **Walt (04W)** generated below 5° North Latitude in the eastern Caroline Islands. Walt was the first super typhoon of the year in the western North Pacific and the only significant tropical cyclone to form in May. It developed as part of an equatorial convective process known as a "westerly burst" (Lander, 1990) at the same time a twin, Tropical Cyclone 21P (Lisa), developed in the Southern Hemisphere. Almost a month later, Typhoon **Yunya (05W)** followed as the first significant tropical cyclone of June, breaking a nearly month-long lull in activity in the western North Pacific. Yunya was noteworthy because a ship transited through its center, providing a unique glimpse of the structure of a rapidly-developing, midget typhoon. Its passage through central Luzon coincided with the massive eruption of Mount Pinatubo and evacuation of personnel from Clark Air Base.

JULY

Two-and-one-half weeks after Yunya dissipated, **Zeke (06W)** evolved in the Philippine Sea. Zeke was the first tropical cyclone to develop during the month of July, and initiated a period of nearly continuous tropical cyclone warning status for JTWC in the Northwest Pacific through early December. Typhoon Zeke made landfall three times before it dissipated over the mountains of northern Vietnam. The second of five tropical cyclones to form in July, **Amy (07W)** followed a west-northwesterly track that paralleled the one taken a week earlier by Typhoon Zeke (06W). Near Taiwan, the typhoon caused the loss of the 16,000 ton freighter, **Blue River**, with its entire crew, and then became the deadliest typhoon of the year to strike China. **Brendan (08W)** was the third straight-runner in a row. Torrential rains associated with the tropical cyclone's passage across northern Luzon unleashed lahars or avalanches of volcanic debris, mud and boulders in the valleys near Mount Pinatubo.

After a succession of three straight-running July typhoons (Zeke (06W), Amy (07W), and Brendan(08W)) which moved west-northwestward, **Caitlin (09W)** became the first cyclone of the season to threaten Japan and Korea. Much-needed heavy rains fell on drought-stricken Okinawa as Caitlin passed west of the island. Then, **Enrique (06E)**, a rare tropical cyclone which began in the Eastern Pacific and trekked 4900 nm (9100 km) across the central North Pacific Ocean, regenerated, reached minimum tropical storm intensity, and then dissipated in the JTWC area of responsibility. Over the past 20 years, Typhoon Georgette (1986) was the only other Eastern Pacific tropical cyclone to cross the international date line.

AUGUST

Doug (10W) was the first of a series of six tropical cyclones to form in August as part of a large NSS monsoon gyre. Doug failed to intensify beyond minimal tropical storm intensity because it moved rapidly northward into an area of colder sea surface temperatures and increased vertical wind shear before transitioning into an extratropical cyclone. The second tropical cyclone of August, **Ellie (11W)**, formed as part of the larger NSS monsoon gyre a day after Doug. Ellie, was also the second midget typhoon of 1991. It maintained a generally westward track, traveling 2400 nm (4440 km) across the western North Pacific from just west of Wake Island to Taiwan. Next came **Fred (12W)** which was spawned by the Asian monsoon trough and became part one of two, three-storm outbreaks that occurred in mid-August. Typhoon Fred skirted the northern coasts of Luzon and Hainan Island before dissipating over Southeast Asia. **Tropical Depression 13W** formed as a low pressure area in the same NSS monsoon gyre as Typhoon Ellie, then tracked northwestward in Ellie's wake. Tropical Depression 13W was marked by large diurnal fluctuations in convection which slowed the development of strong surface winds. The fourth and largest of six tropical cyclones generated by the NSS monsoon gyre active during the month of August was Typhoon **Gladys (14W)**. Gladys' wind field expanded dramatically with only a small change in minimum sea-level pressure as it tracked south of Korea and western Japan. Gladys was a good example of a cyclone that "strengthened" but did not "intensify" significantly. When animated satellite imagery indicated cyclonic turning in an area of deep convection associated with the NSS monsoon gyre, a Significant Tropical Weather Advisory was reissued at 212200Z (August) to include the disturbance that was to become **Tropical Depression 15W**. Five days later **Harry (16W)** became the last of six tropical cyclones, beginning with Doug (10W) three weeks earlier, to generate within this NSS monsoon gyre.

SEPTEMBER THROUGH DECEMBER

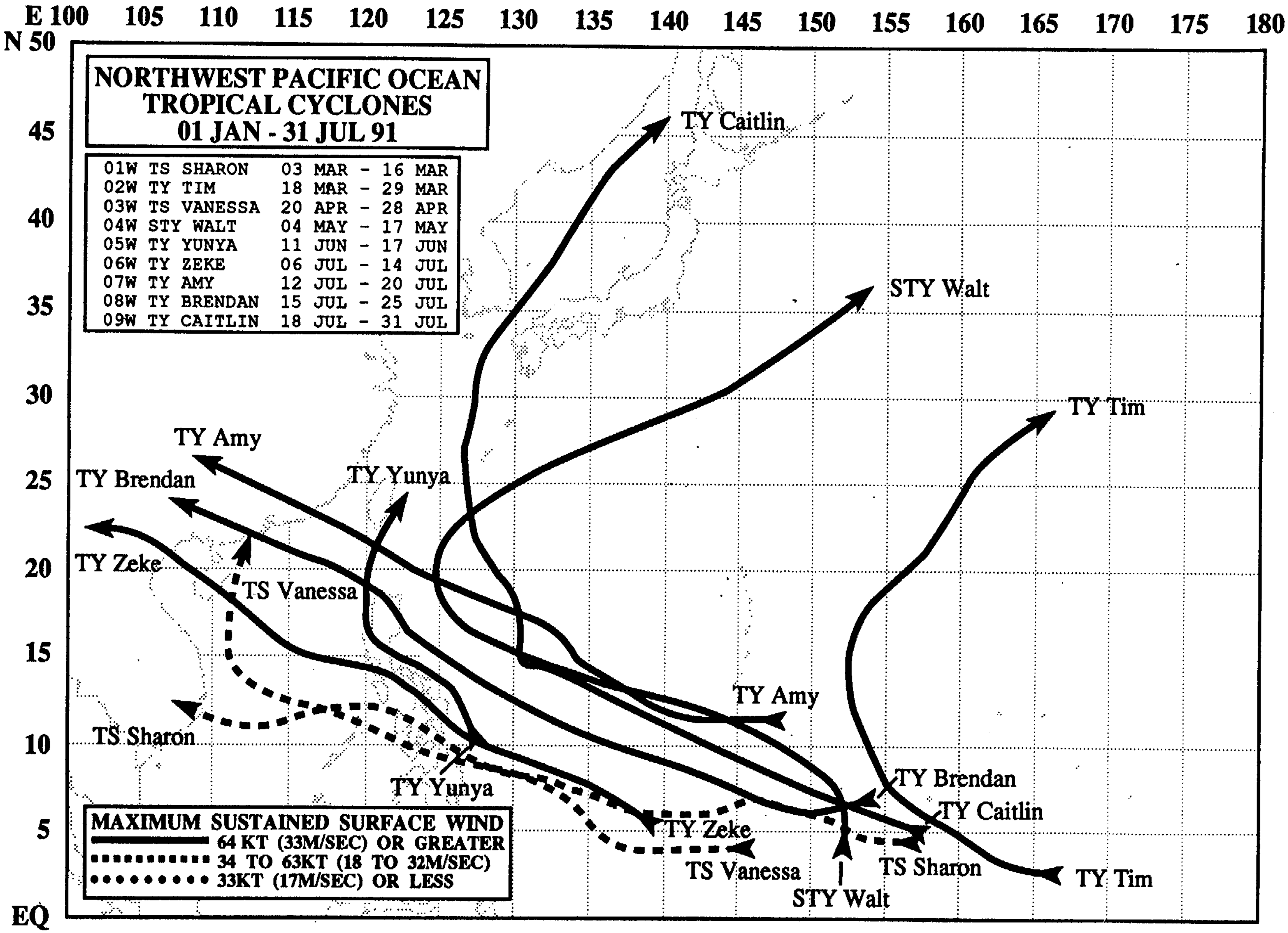
Ivy (17W) was the first tropical cyclone since Fred to form in the monsoon trough which re-established itself eastward from Asia through the Caroline Islands. Ivy was also the first significant threat of the typhoon season for the Mariana Islands. For 4 days, the tropical cyclone tracked west-northwestward, straight towards Guam, then on 4 September it took a sudden, unanticipated turn to the north-northwest and headed for the Northern Marianas and subsequently Japan. **Joel (18W)** developed in the South China Sea, tracked westward, and then came to an abrupt halt. After little, or no, movement for six hours, the tropical cyclone slowly inched northward and made landfall 70 nm (130 km) east of Hong Kong. A day later, **Kinna (19W)** formed in the western Caroline Islands. It was the most destructive tropical cyclone to strike Okinawa since 1987, and the first typhoon to pass directly across the island since Vera in 1986. Later, the typhoon also passed directly across Sasebo, Japan, and caused extensive damage on Kyushu and later Honshu as it raced northeastward after recurvature. The exceptionally accurate forecasts of the path taken by Typhoon Kinna provided more than ample lead time for disaster preparation at key DOD installations. As Kinna became extratropical, Tropical Storm **Luke (20W)** formed just east of the Mariana Islands. It was a broad monsoonal cyclone, difficult to track by satellite, and had the largest initial position errors of the season. Luke's unusual recurvature track resulted from the extension of the mid-latitude, mid-tropospheric westerlies deep into the tropics in mid-September, which temporarily broke down the subtropical ridge in the western Pacific.

Mireille (21W) was part of a three storm outbreak in September consisting of Tropical Storm Luke (20W) and Typhoon Nat (22W). Later, after Luke had become extratropical, Mireille, Nat and Typhoon Orchid (23W) became part of another three storm outbreak. Mireille was the second super typhoon of the year in the Northwest Pacific, and became the worst storm to strike Japan in three decades. It outgrew it's early midget size after passing Saipan, and reached super typhoon intensity several days before threatening Okinawa. Recurving just to the southwest of Okinawa, the typhoon accelerated, cutting a path across western Kyushu and Honshu. Over the Sea of Japan, Mireille transitioned into an intense extratropical cyclone which slammed into northern Honshu and southern Hokkaido producing gusts to 83 kt (43 m/sec) at Misawa AB. For 17 days, Typhoon **Nat (22W)** exhibited highly erratic behavior which included four major track changes, two intensification episodes, and two landfalls. It persisted longer than any other western North Pacific tropical cyclone during 1991, requiring a total of 61 warnings which was only 18 warnings shy of the all-time record set by Typhoon Rita (1972). Nat's track and behavior were reminiscent of that of Typhoon Wayne (1986).

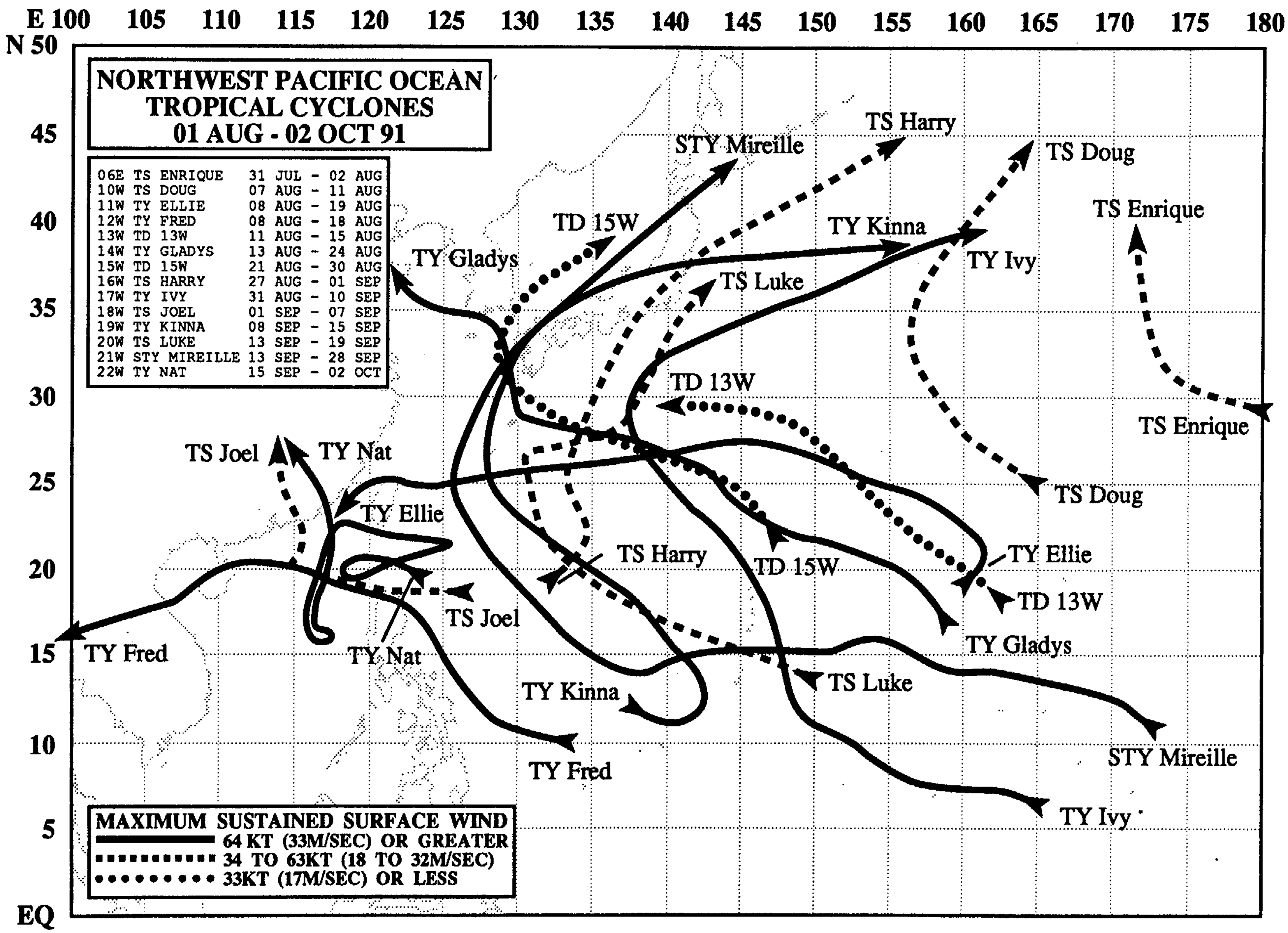
Typhoon **Orchid (23W)** was the first tropical cyclone to develop during the month of October, and was followed within a day by Typhoon Pat (24W). As these two typhoons interacted, Orchid slowed about 200 nm (370 km) off the coast of Japan, and caused widespread flooding in Tokyo and surrounding cities. Developing at the same time in early October as Orchid, Typhoon **Pat's (24W)** track paralleled that of Orchid's, but several hundred miles to the east. Pat's rapid intensification phase was correctly predicted by a recently developed pixel-counting forecast scheme. Two days after Orchid and Pat went extratropical east of Japan, **Ruth (25W)** developed in the eastern Caroline Islands. Super Typhoon Ruth was the second most intense tropical cyclone of 1991. Climatological analogs enabled forecasters to anticipate Ruth's rapid deepening to super typhoon intensity in the Philippine Sea. However, track forecasts based on the NOGAPS spectral model were 2 days early in predicting recurvature. This resulted in the largest forecast track errors of the year as Ruth slammed into northern Luzon instead of recurving toward the Ryukyu Islands. As Ruth finally recurved, Super Typhoon **Seth (26W)** started cranking up in the southern Marshall Islands. It was the first of six tropical cyclones of at least typhoon intensity to occur in the month of November. This was the most active November in the western North Pacific since 1964 when six occurred. Forecasts for Seth's generally westward track were complicated by the normally reliable objective guidance, that in Seth's case, indicated recurvature which did not occur. When Seth formed, **Thelma (27W)** slowly intensified in the central Caroline Islands. The worst loss of life due to a natural disaster in the western North Pacific during 1991 occurred when Tropical Storm Thelma made landfall in the central Philippine islands. News accounts estimated that 6000 people died and 20,000 people were made homeless by landslides, flash flooding, and the failure of a dam. The highest casualties occurred on Leyte and Negros Islands where widespread logging had stripped the hills bare of vegetation.

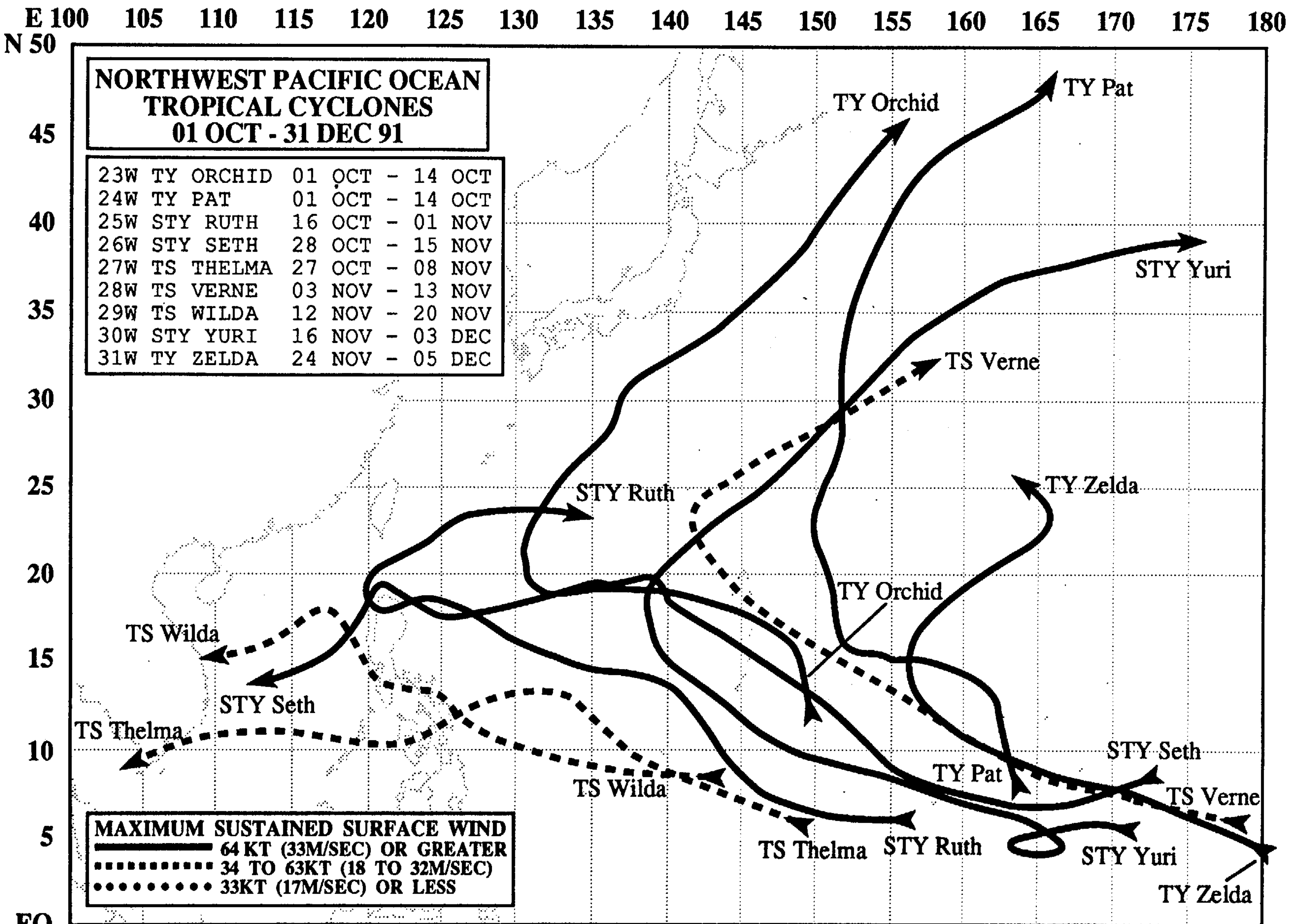
On 3 November, westerly low-level

winds along the equator and a persistent cloud system near the international date line generated the tropical disturbance which eventually became Tropical Storm **Verne (28W)**. Tropical Storm Verne passed between Pagan and Agrihan in the northern Mariana Islands with a maximum intensity of 55 kt (28 m/sec), and closed to within 800 nm (1480 km) of Super Typhoon Seth (26W) on 10 November, before recurving northeastward on 11 November. As Verne transitioned into an extratropical low, **Wilda (29W)** got started in the western Caroline Islands. Tropical Storm Wilda was another midget tropical cyclone, and posed another serious threat to the central Philippine Islands which were devastated by Tropical Storm Thelma (27W) only 2 weeks before. Wilda maintained its peak intensity of 45 kt (23 m/sec) as it tracked across southern Luzon and passed about 40 nm (75 km) south of Manila around noon on 17 November. Due to its compact wind field, damage was minimal near Manila. After turning northwestward later on 17 November, Wilda began to weaken, and on 19 November the residual low-level circulation drifted southwestward with the prevailing northeast monsoon. By the time Wilda had dissipated, **Yuri (30W)** had formed in the southern Marshall Islands and was slowly intensifying. Super Typhoon Yuri was the most intense tropical cyclone of the year, with maximum sustained winds estimated at 150 kt (77 m/sec) and an estimated minimum sea-level pressure of 885 mb. It also was the most intense cyclone to pass within 60 nm (110 km) of Guam since Typhoon Karen (1962). Yuri's steady rate of intensification to a super typhoon without an episode of explosive deepening was unusual. High water and waves caused extensive damage to low-lying areas in the southeastern part of Guam. Yuri was also the largest typhoon to affect the western North Pacific in many years, growing to a diameter of over 900 nm (1665 km) a day after passing Guam. As Yuri bore down on Guam, **Zelda (31W)** developed in low latitudes near the international date line. Typhoon Zelda was the last tropical cyclone of the year, and the fifth midget. Intensification during the early stages of its development was overlooked because of its very small size. Zelda caused considerable damage to the lightly constructed buildings and homes on Kwajalein and the nearby islands and atolls, and caused several injuries.

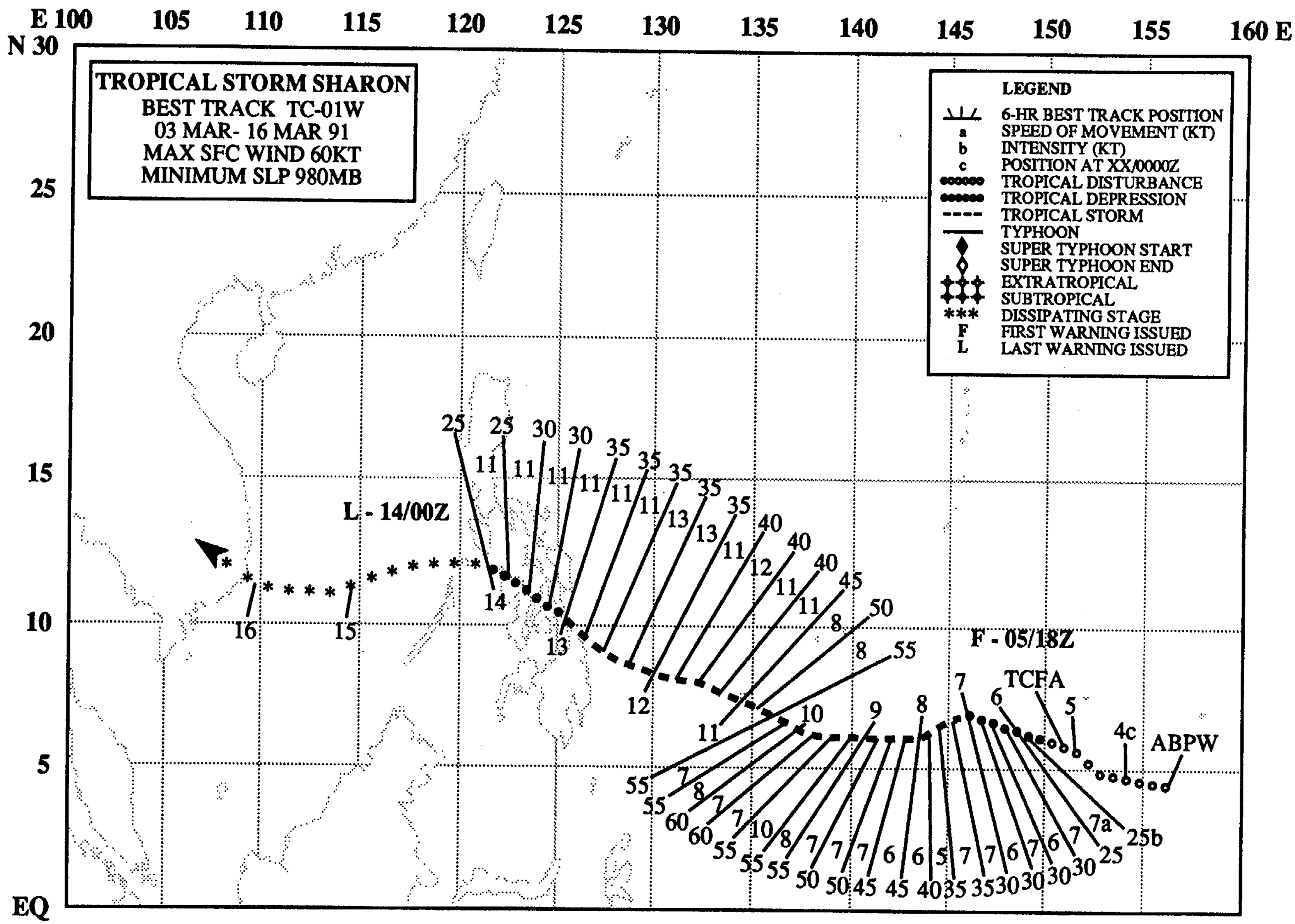


NORTHWEST PACIFIC OCEAN
TROPICAL CYCLONES
01 JAN - 31 JUL 91
01W TS SHARON 03 MAR - 16 MAR
02W TY TIM 18 MAR - 29 MAR
03W TS VANESSA 20 APR - 28 APR
04W STY WALT 04 MAY - 17 MAY
05W TY YUNYA 11 JUN - 17 JUN
06W TY ZEKE 06 JUL - 14 JUL
07W TY AMY 12 JUL - 20 JUL
08W TY BRENDAN 15 JUL - 25 JUL
09W TY CAITLIN 18 JUL - 31 JUL
MAXIMUM SUSTAINED SURFACE WIND
64 KT (33M/SEC) OR GREATER
34 TO 63KT (18 TO 32M/SEC)
33KT (17M/SEC) OR LESS
E 100 105 110 115 120 125 130 135 140 145 150 155 160 165 170 175 180
N 50 45 40 35 30 25 20 15 10 5 EQ
TY Caitlin
STY Walt
TY Tim
TY Amy
TY Brendan
TY Yunya
TY Zeke
TS Vanessa
TS Sharon
TY Amy
TY Yunya
TY Brendan
TY Caitlin
TY Zeke
TS Vanessa
TS Sharon
TY Tim
STY Walt


NORTHWEST PACIFIC OCEAN
TROPICAL CYCLONES
01 AUG - 02 OCT 91
06E TS ENRIQUE 31 JUL - 02 AUG
10W TS DOUG 07 AUG - 11 AUG
11W TY ELLIE 08 AUG - 19 AUG
12W TY FRED 08 AUG - 18 AUG
13W TD 13W 11 AUG - 15 AUG
14W TY GLADYS 13 AUG - 24 AUG
15W TD 15W 21 AUG - 30 AUG
16W TS HARRY 27 AUG - 01 SEP
17W TY IVY 31 AUG - 10 SEP
18W TS JOEL 01 SEP - 07 SEP
19W TY KINNA 08 SEP - 15 SEP
20W TS LUKE 13 SEP - 19 SEP
21W STY MIREILLE 13 SEP - 28 SEP
22W TY NAT 15 SEP - 02 OCT
MAXIMUM SUSTAINED SURFACE WIND
64 KT (33M/SEC) OR GREATER
34 TO 63KT (18 TO 32M/SEC)
33KT (17M/SEC) OR LESS
E 100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
N 50
45
40
35
30
25
20
15
10
5
EQ
STY Mireille
TS Harry
TS Doug
TS Enrique
TD 15W
TY Kinna
TY Gladys
TY Ivy
TS Luke
TD 13W
TS Enrique
TS Joel
TY Nat
TY Ellie
TS Doug
TS Harry
TY Ellie
TD 15W
TD 13W
TS Joel
TY Fred
TY Nat
TY Gladys
TS Luke
TY Kinna
TY Fred
STY Mireille
TY Ivy


NORTHWEST PACIFIC OCEAN
TROPICAL CYCLONES
01 OCT - 31 DEC 91
23W TY ORCHID 01 OCT - 14 OCT
24W TY PAT 01 OCT - 14 OCT
25W STY RUTH 16 OCT - 01 NOV
26W STY SETH 28 OCT - 15 NOV
27W TS THELMA 27 OCT - 08 NOV
28W TS VERNE 03 NOV - 13 NOV
29W TS WILDA 12 NOV - 20 NOV
30W STY YURI 16 NOV - 03 DEC
31W TY ZELDA 24 NOV - 05 DEC
MAXIMUM SUSTAINED SURFACE WIND
64 KT (33M/SEC) OR GREATER
34 TO 63KT (18 TO 32M/SEC)
33KT (17M/SEC) OR LESS
E 100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
N 50
45
40
35
30
25
20
15
10
5
EQ
TY Orchid
TY Pat
STY Yuri
TS Verne
TY Zelda
STY Ruth
TY Orchid
TS Wilda
STY Seth
TS Thelma
TS Wilda
TS Thelma
STY Ruth
TY Pat
STY Seth
TS Verne
STY Yuri
TY Zelda

Intentionally left blank.


TROPICAL STORM SHARON
BEST TRACK TC-01W
03 MAR- 16 MAR 91
MAX SFC WIND 60KT
MINIMUM SLP 980MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
L - 14/00Z
F - 05/18Z
TCFA
ABPW
E 100
105
110
115
120
125
130
135
140
145
150
155
160 E
N 30
25
20
15
10
5
EQ

TROPICAL STORM SHARON (01W)

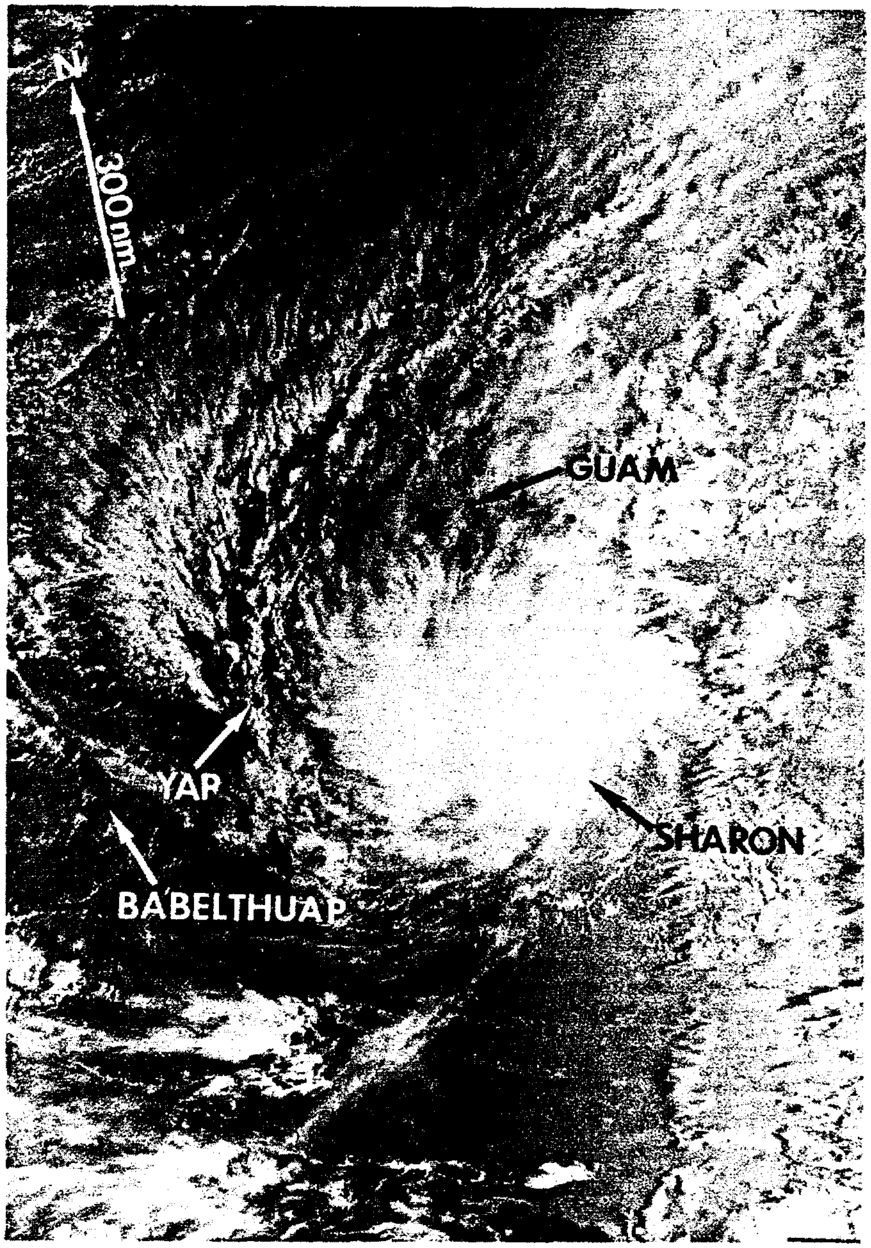
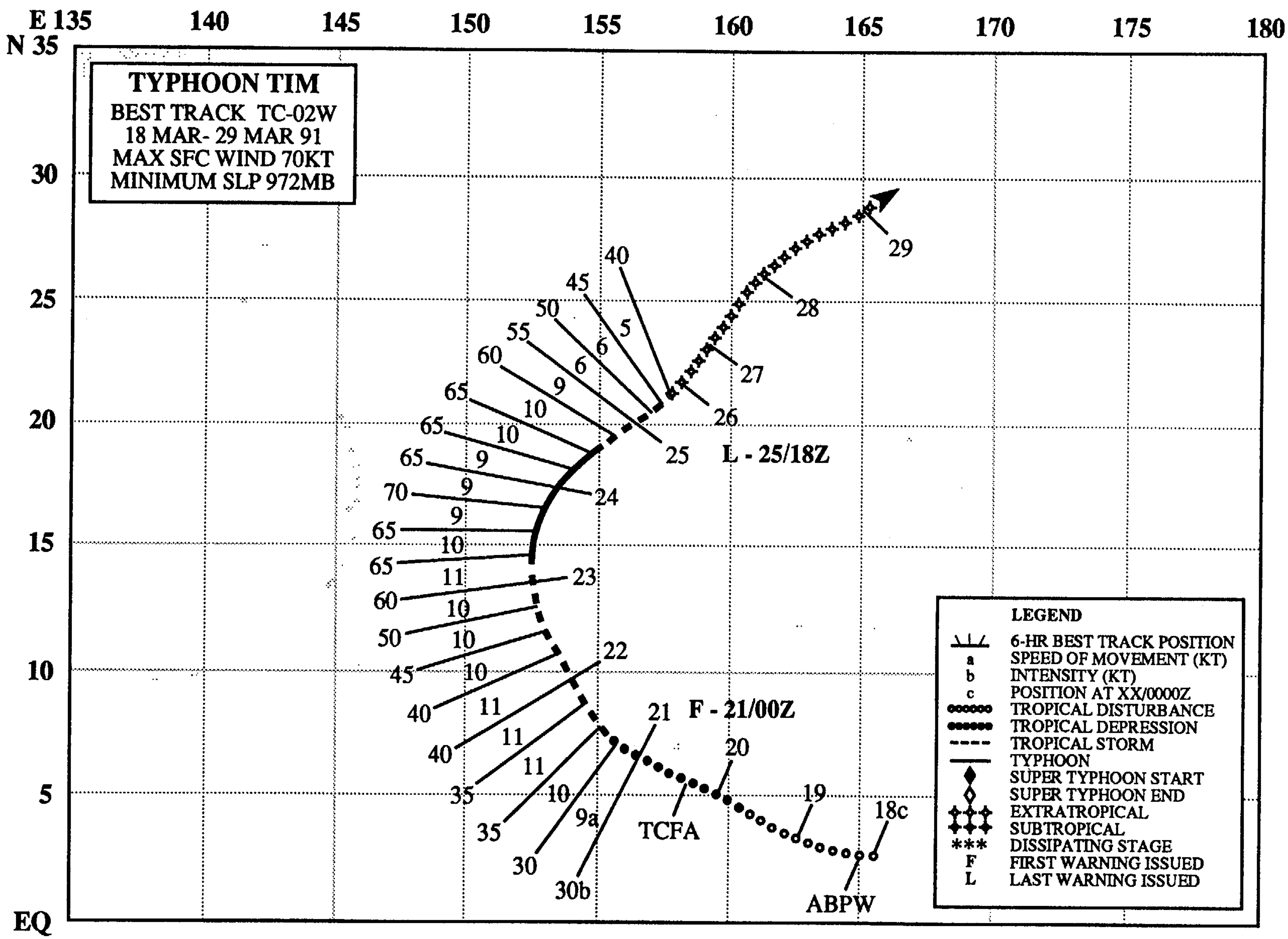


Figure 3-01-1. Tropical Storm Sharon near peak intensity east of Yap (062234Z March DMSP visual imagery).

Sharon, the first tropical cyclone of 1991 in the western North Pacific, developed the first week of March in conjunction with a burst of low-level westerly winds that extended eastward along the equator from New Guinea to the international date line. Its persistent convection was initially discussed on the 030600Z Significant Tropical Weather Advisory. Increased deep convection around the partially exposed low-level circulation center prompted the issuance of the 050451Z Tropical Cyclone Formation Alert. The tropical cyclone developed slowly due to persistent upper level shear on the eastern side of the convective cloud mass. The first warning, valid at 051800Z, did not forecast further intensification to a tropical storm because of the amount of shear evident from satellite imagery. However, as Sharon tracked steadily westward, it reached a peak intensity of 60 kt (30 m/sec) south of Yap before the central dense overcast sheared apart east of Belau. Koror (WMO 91408) reported light winds as the broad circulation center passed over Belau on 11 March, then the sustained surface winds increased to 30 kt (15 m/sec) as Sharon moved west of the station. Later, as the tropical cyclone continued to weaken over the central Philippine Islands, JTWC issued the final warning at 140000Z. The remnants of Sharon continued westward across the South China Sea and dissipated over southeastern Vietnam on 16 March.


TYPHOON TIM
BEST TRACK TC-02W
18 MAR- 29 MAR 91
MAX SFC WIND 70KT
MINIMUM SLP 972MB
E 135
140
145
150
155
160
165
170
175
180
N 35
30
25
20
15
10
5
EQ
L - 25/18Z
F - 21/00Z
TCFA
ABPW
18c
19
20
21
22
23
24
25
26
27
28
29
30b
9a
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TYPHOON TIM (02W)

I. HIGHLIGHTS

Tim was the second tropical cyclone to develop in the eastern Caroline Islands during the month of March. It was the first March typhoon since 1982, and marked only the third time since the Joint Typhoon Warning Center was established in 1959 that multiple storms occurred in March. The recurvature track taken by Tim proved to be a difficult challenge for JTWC forecasters to predict, because the primary prognostic guidance was slow to predict the changing synoptic situation. Average forecast errors for Tim were the largest of any Northwest Pacific tropical cyclone forecast in 1991.

II. TRACK AND INTENSITY

As the Southern Hemisphere Tropical Cyclone, 16P (Cynthia), intensified in the Coral Sea on 18 March, analysis of the surface and gradient-level wind flow in the tropics indicated that a westerly surge was again established along the equator east of New Guinea. Just two weeks after Sharon (01W) formed in the eastern Caroline Islands, the near-equatorial trough reestablished itself in the same area with associated pressure falls and increased cloudiness. The first mention of a developing tropical disturbance (Tim) appeared on the 18 March Significant Tropical Weather Advisory. Later, based on a 38 kt (20 m/sec) gradient-level wind at Pohnpei (WMO 91348) and a 2-day pressure fall of 2 to 3 mb, a Tropical Cyclone Formation Alert was issued at 200500Z. The first warning on Tropical Depression 02W followed at 210000Z when satellite imagery located a poorly defined cloud vortex that was aligned with the synoptic data.

As it tracked northwestward, Tim was upgraded to a tropical storm at 211800Z due to an increase in the amount of deep convection. The track became more northerly as a series of fast-moving short waves in the polar westerlies eroded the narrow subtropical ridge, allowing Tim to move towards the break in the ridge. At 230600Z, typhoon intensity was attained when Tim developed a large, ragged eye (Figure 3-02-1). Tim arrived at its point of recurvature 420 nm (780 km) east of Saipan. Twelve hours after recurvature, the typhoon reached a peak intensity of 70 kt (35 m/sec) and then began to weaken gradually due to increased vertical shear. Tim transitioned to an extratropical low on 25 March.

III. FORECAST PERFORMANCE

JTWC's larger than average overall forecast errors on this typhoon were a consequence of over-reliance on guidance from its primary aids (Figure 3-02-2) which weren't representative of the changing synoptic situation. Initially, the majority of JTWC's forecast aids indicated Tim would move along a climatologically favored west-northwestward track, steered by the flow south of the narrow subtropical ridge. Post-analysis of the synoptic situation showed that Typhoon Tim tracked north-northwestward into a neutral point in the subtropical ridge located east of Saipan. This neutral point was identified in the 200000Z NOGAPS prognostic series used to develop the first warning, but based on the depiction of the forecast aids, recurvature was not considered a likely scenario. Recurvature was discussed as a moderate probability alternate scenario on JTWC's first warning, but when the dynamic aids OTCM and FBAM continued to indicate Tim would turn to the west and remain south of the ridge axis, the recurvature philosophy was discarded in favor of a "stairstep" track which agreed more closely with the prognostic aids. Supporting NOGAPS prognostic fields indicated the portion of the subtropical ridge east of the neutral point would build westward (and to the north of the cyclone) and cause Tim to continue moving northwestward. JTWC warnings reflected this forecast reasoning, and as a result, failed to identify in the early stages of development that Tim's more northward motion was a precursor to recurvature. In particular, JTWC's overall best performing forecast aid, OTCM, missed the recurvature point entirely.

Typhoon Tim intensified at a normal rate of development, and its intensification and extratropical transition were well forecast by JTWC.

IV. IMPACT

No reports of significant damage or loss of life were received as Tim remained over open ocean well away from land during its life.

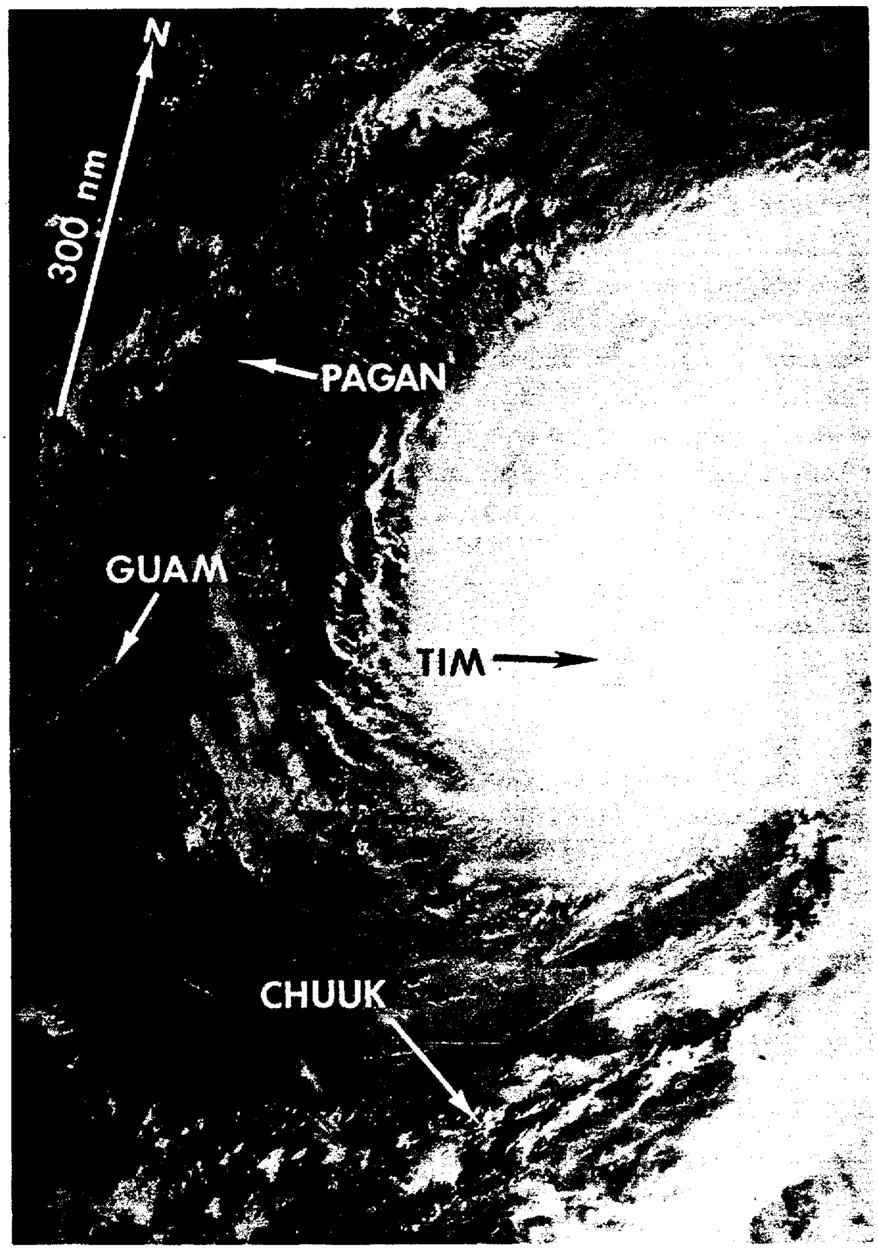


Figure 3-02-1. Satellite imagery of the large, cloud-filled eye of Typhoon Tim approximately 12 hours prior to reaching maximum intensity (230431Z March NOAA visual imagery).

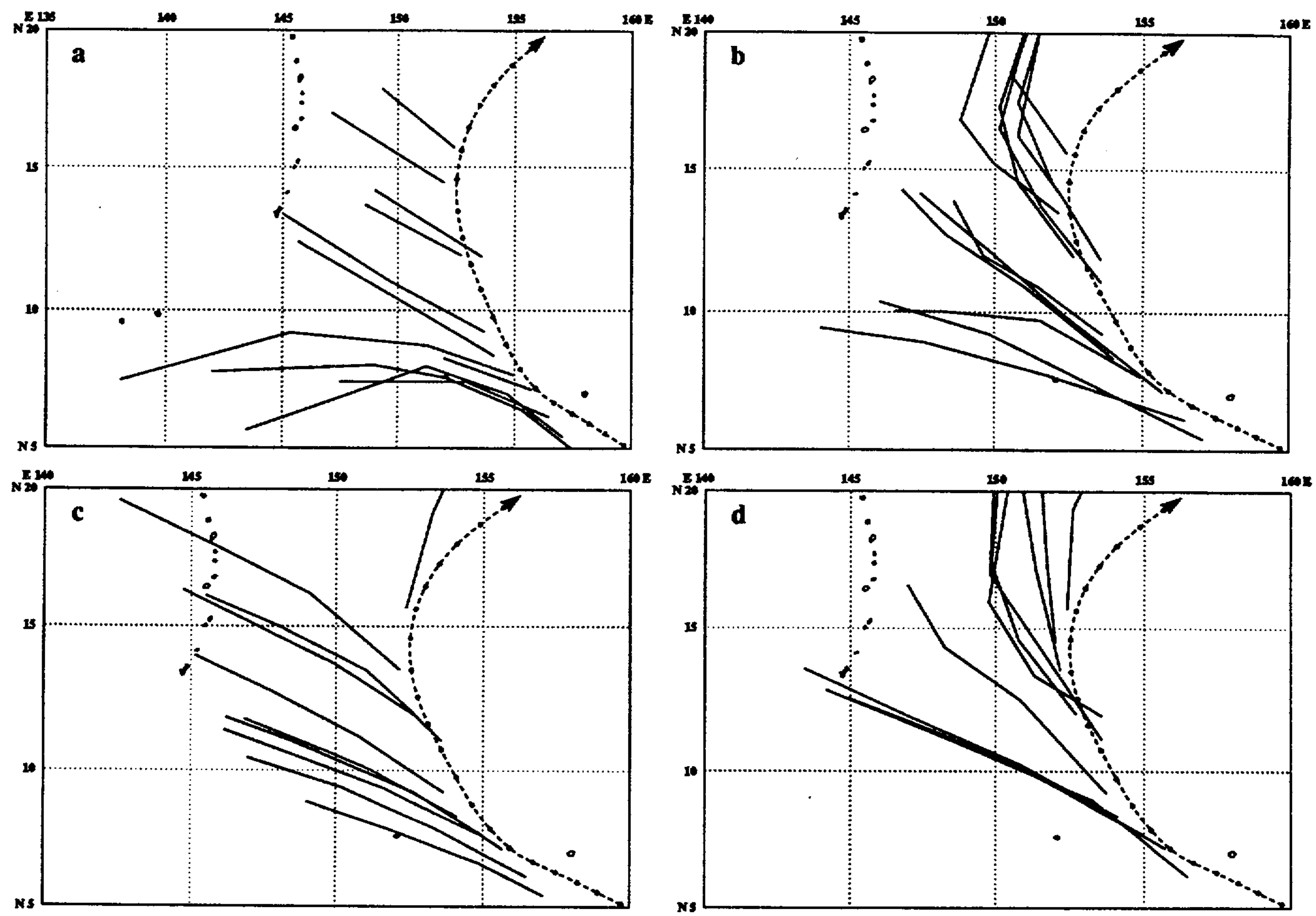
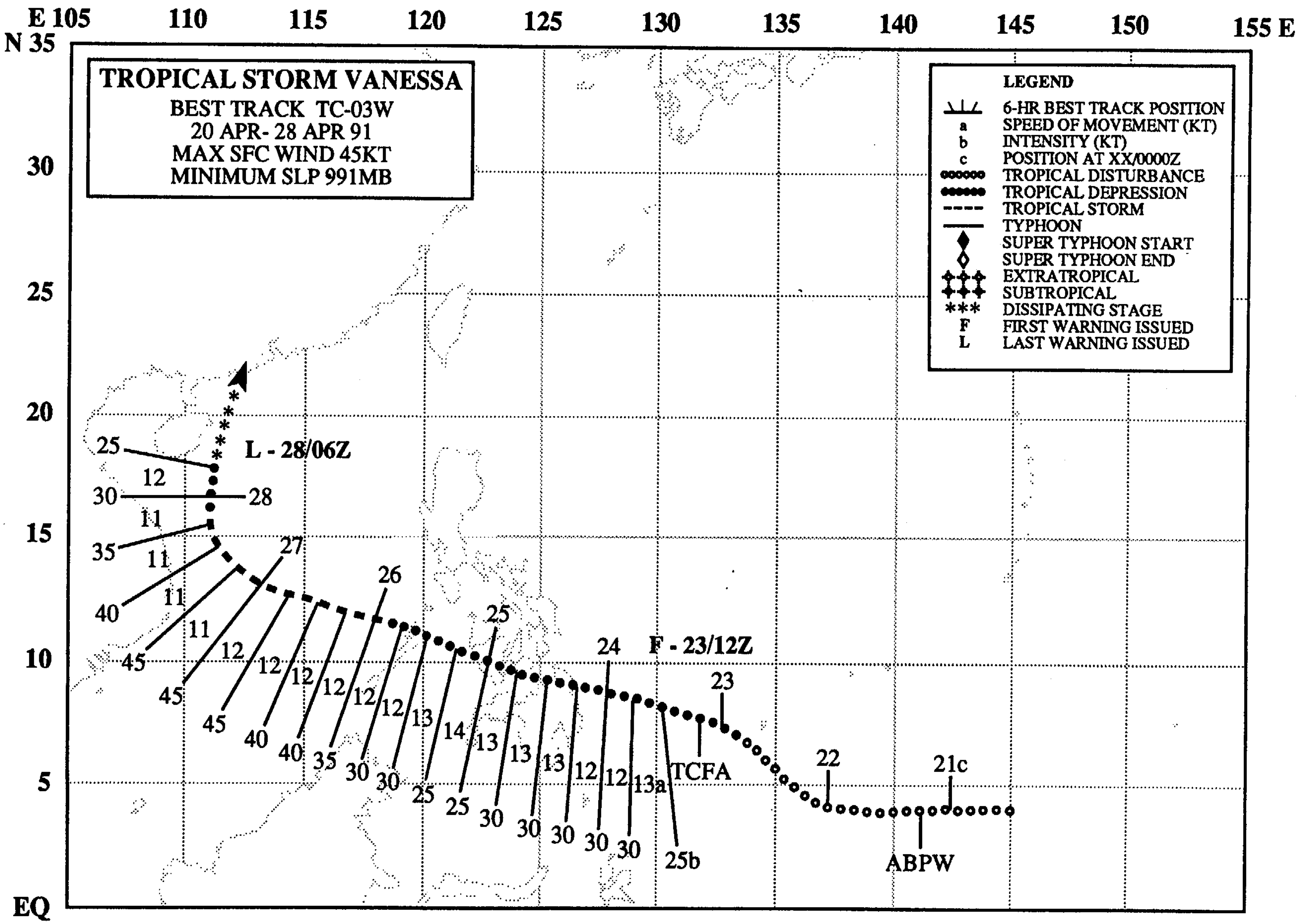


Figure 3-02-2. JTWC's primary forecast aids [a) OTCM, b) FBAM, and c) the CSUM] remained consistently left of track. While the official JTWC forecasts [d) JTWC] were consistently to the right of the other aids, in retrospect, they were not far enough to the right.


TROPICAL STORM VANESSA
BEST TRACK TC-03W
20 APR- 28 APR 91
MAX SFC WIND 45KT
MINIMUM SLP 991MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 105
110
115
120
125
130
135
140
145
150
155 E
N 35
30
25
20
15
10
5
EQ
L - 28/06Z
F - 23/12Z
TCFA
ABPW
21c
22
23
24
25
26
27
28
13a
25b

TROPICAL STORM VANESSA (03W)

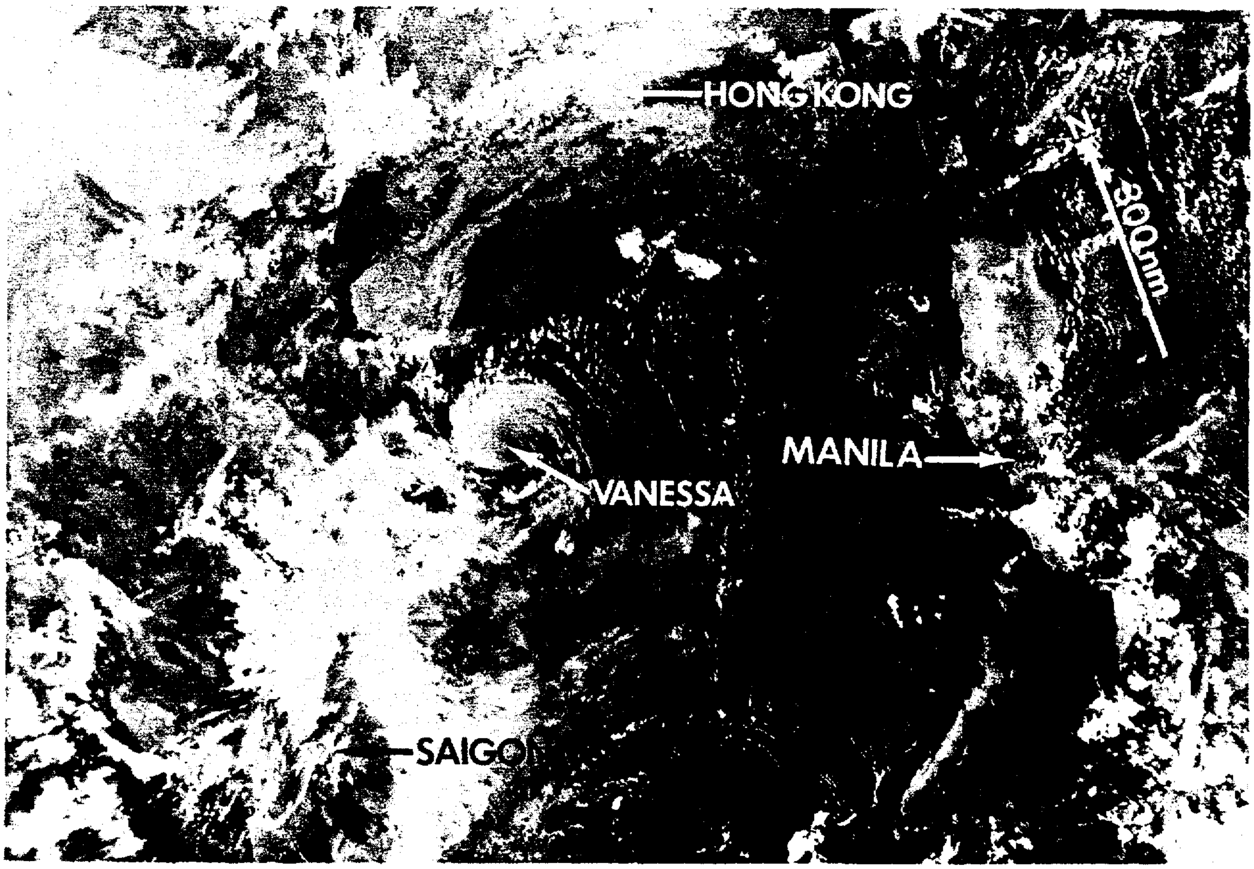
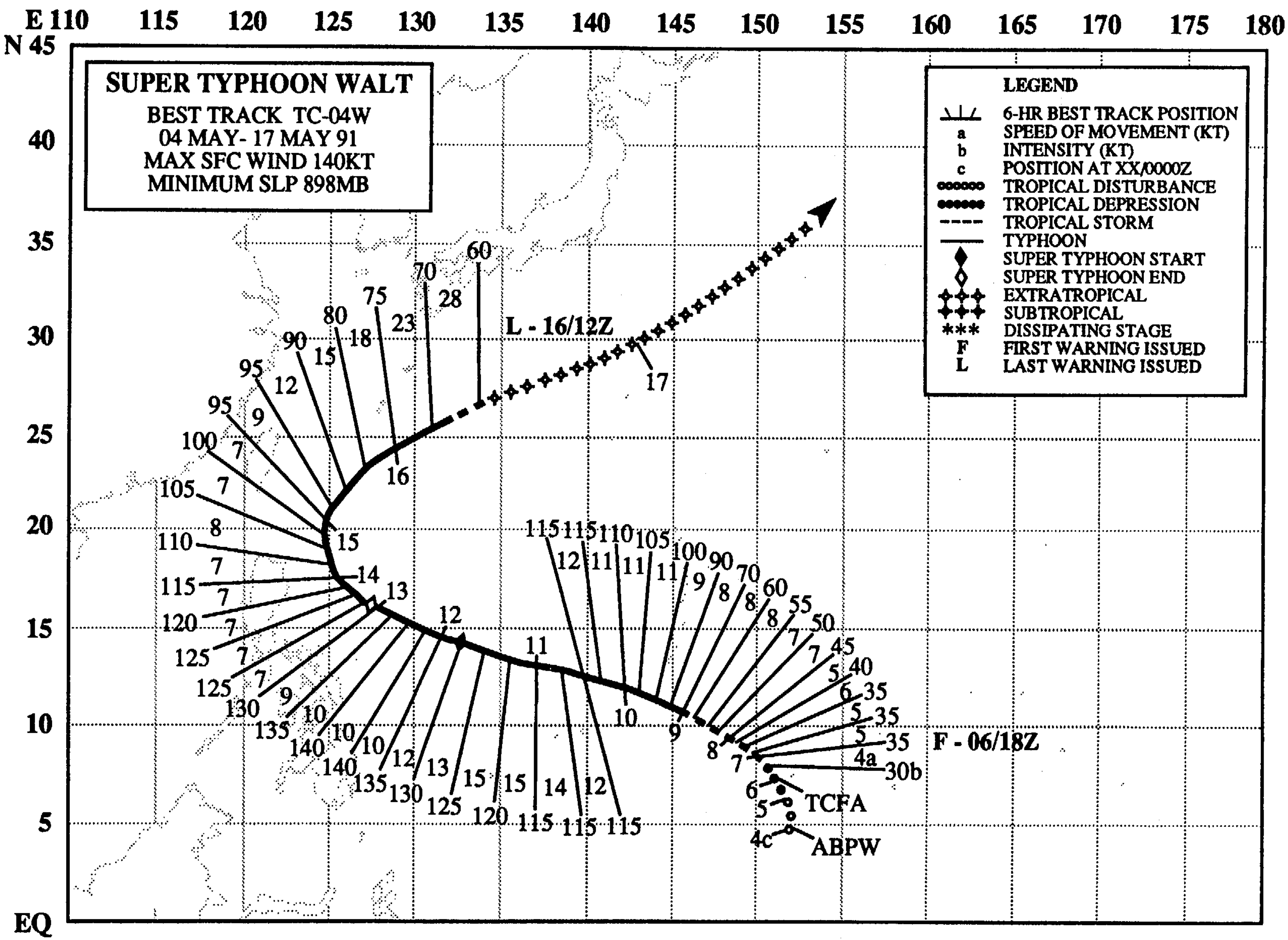


Figure 3-03-1 The exposed low-level center of Tropical Storm Vanessa approaches the coast of Vietnam (271905Z NOAA April enhanced infrared imagery).

After Typhoon Tim (02W) in mid-March, the near-equatorial trough remained relatively inactive until Vanessa's convection flared up to the south of Guam over a month later. This disturbance with its persistent convection was first mentioned in the Significant Tropical Weather Advisory on 21 April. A Tropical Cyclone Formation Alert was issued at 230500Z when animated satellite imagery revealed that individual thunderstorms had started rotating cyclonically about a singular point. At 231200Z, the alert was followed by the first warning on Tropical Depression 03W, based on a 30 kt (15 m/sec) ship report. Vanessa did not intensify as it tracked south of the subtropical ridge and across the central Philippines. Twenty-four hours after leaving the Philippine Islands, it reached tropical storm intensity at 260000Z, based on a satellite intensity estimate of 35 kt (18 m/sec). Vanessa peaked at 45 kt (23 m/sec) in the South China Sea at 261800Z. Less than a day later, vertical wind shear caused Tropical Storm Vanessa to weaken rapidly. Satellite imagery showed that Vanessa had completely lost its deep central convection. This prompted the JTWC to issue its final warning at 280600Z. Embedded in the prevailing low-level flow, the remnants of Tropical Storm Vanessa moved northward through the axis of the subtropical ridge, and dissipated southwest of Hong Kong.


SUPER TYPHOON WALT
BEST TRACK TC-04W
04 MAY- 17 MAY 91
MAX SFC WIND 140KT
MINIMUM SLP 898MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
N 45
40
35
30
25
20
15
10
5
EQ
L - 16/12Z
F - 06/18Z
TCFA
ABPW

SUPER TYPHOON WALT (04W)

I. HIGHLIGHTS

Walt was the first super typhoon in the western North Pacific this year and the only significant tropical cyclone to form in May. It developed as part of an equatorial convective process known as a "westerly burst" (Lander, 1990) at the same time a twin, Tropical Cyclone 21P (Lisa), developed in the Southern Hemisphere.

II. TRACK AND INTENSITY

The cloud system that was to become Walt developed in low latitudes in the eastern Caroline Islands in tandem with Tropical Cyclone 21P (Lisa) in the Southern Hemisphere in the Coral Sea. The evolution of these twins is graphically portrayed as cloud silhouettes in Figure 3-04-1. The tropical disturbance initially tracked northwestward towards a weakness in the subtropical ridge north of Guam. However, the subtropical ridge strengthened, built westward, and forced Walt to take a more west-northwesterly track. The tropical cyclone kept on this course for ten days until recurvature occurred early on 15 May. Then, Walt interacted with the polar westerlies aloft and accelerated east-northeastward. Extratropical transition occurred on 16 May as Walt merged with a passing frontal system.

In review, the persistence of Walt's convection prompted first mention on the Significant Tropical Weather Advisory at 040600Z. At 060200Z, a Tropical Cyclone Formation Alert followed the report of a 23 kt (12 m/sec) gradient-level wind at Chuuk (WMO 91334) and a 30 kt (15 m/sec) ship report. Cyclonic rotation of the convective cloud elements on the animated satellite imagery and 20-30 kt (10-15 m/sec) synoptic reports resulted in the issuance of the first warning at 061800Z. The upgrade to tropical storm intensity at 070000Z resulted from a Dvorak intensity estimate increase and another 30 kt (15 m/sec) ship report. A typhoon intensity estimate resulting from the appearance of a ragged eye prompted a warning upgrade to typhoon at 090000Z. Intensification continued, reaching a peak of 140 kt (70 m/sec) at 120600Z. As Walt approached the axis of the subtropical ridge, the vertical shear increased and the typhoon's cloud shield elongated southwest to northeast (Figure 3-04-2). Slow weakening set in and continued through extratropical transition which occurred at 161800Z.

III. FORECAST PERFORMANCE

The overall track errors were 70 nm (130 km), 150 nm (275 km) and 225 nm (420 km) for the 24-, 48-, and 72-hour forecast, respectively. OTCM, CSUM and NOGAPS also did well and demonstrated skill in comparison with CLIPER.

The intensity forecasts were not as skillful. Although rapid intensification and peaking at super typhoon intensity were discussed early in the prognostic reasoning messages, it remained an alternate scenario. However, once rapid intensification began, JTWC did do a much better job of forecasting peak intensity and the weakening trend. Accurate forecasts near Guam prevented DOD and the Government of Guam from taking expensive unnecessary precautions saving upwards of US$3 million.

IV. IMPACT

Even though Walt passed near Guam, northern Luzon and Okinawa, no reports of significant damage were received.

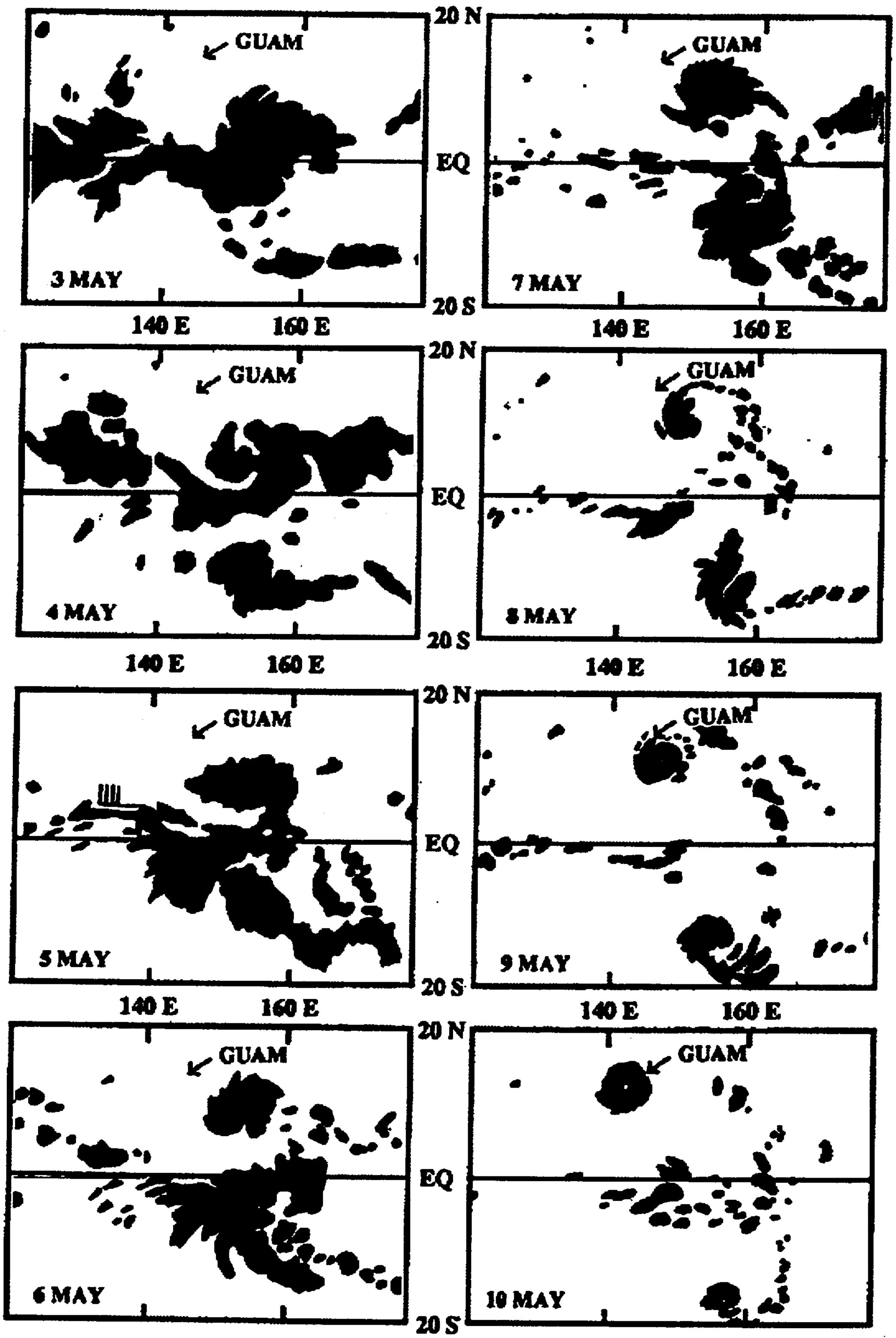


Figure 3-04-1. Silhouettes of deep cloudiness are associated with the "westerly burst" for the period 03 to 10 May. A 40 kt (20 m/sec) ship report, which also cited blowing spray, near the equator on 05 May is unusually strong. As the equatorial convection and westerlies decrease on 7 May, the cloudiness consolidates in the twin cyclones in opposite hemispheres.

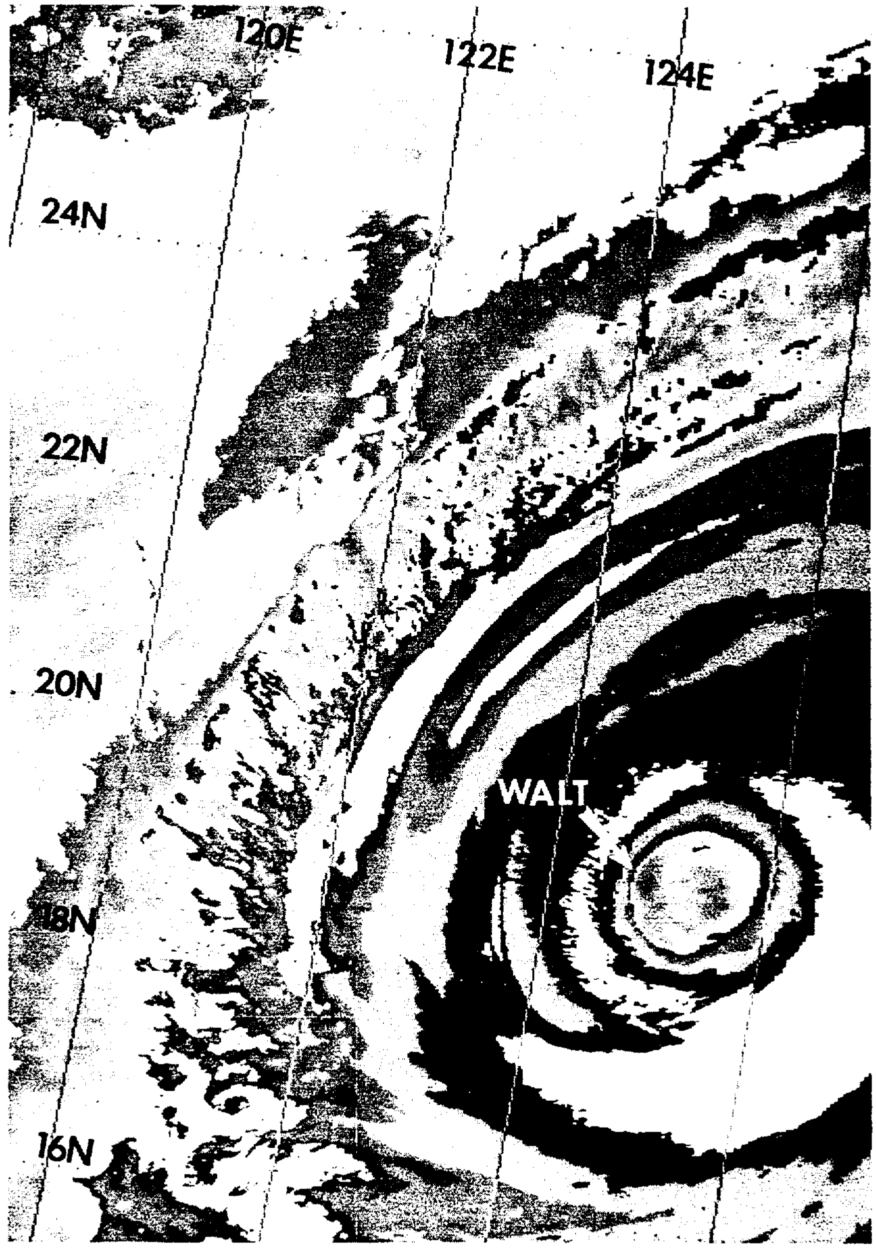
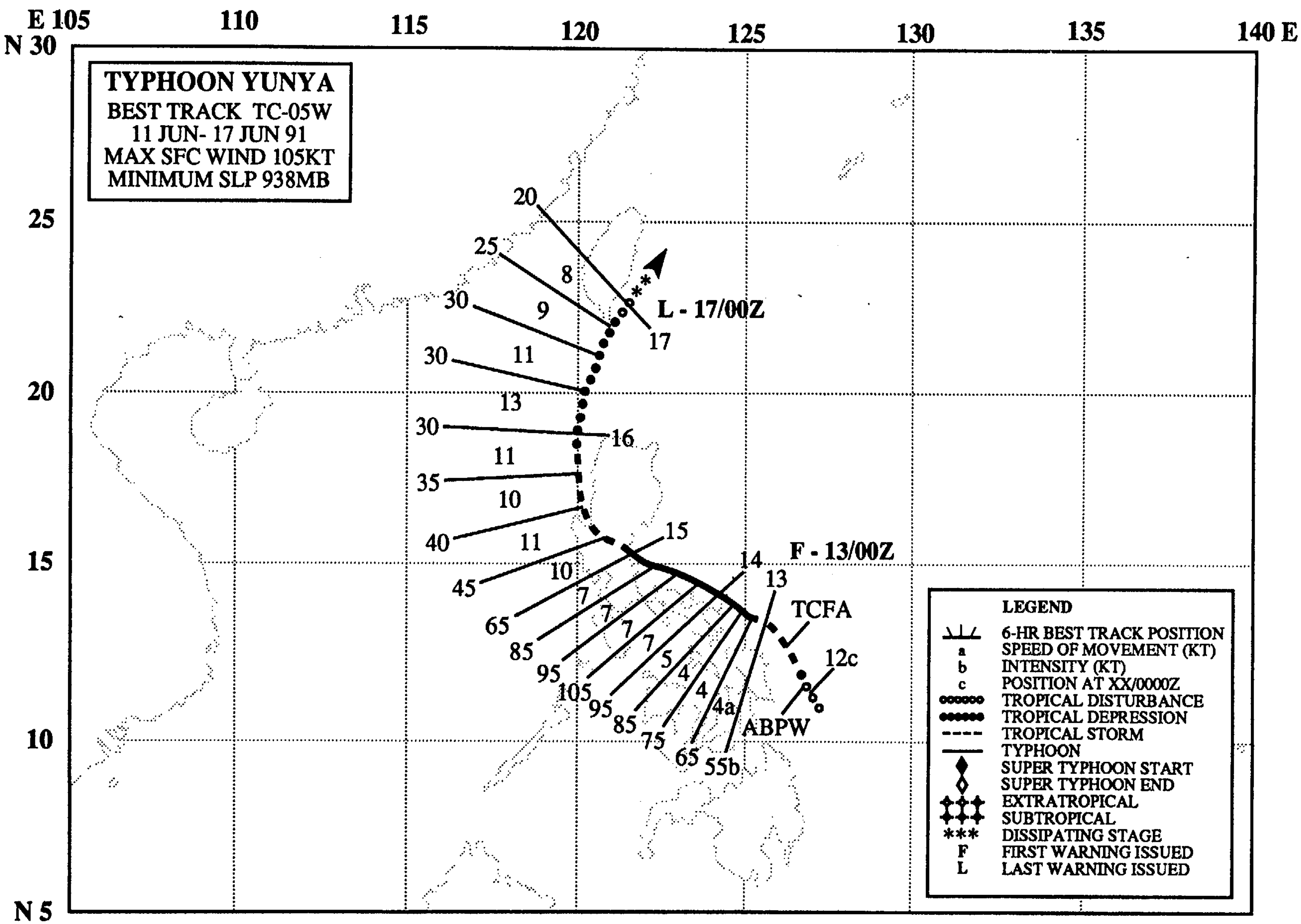


Figure 3-04-2. Walt shows first indications of vertical shear on system forcing the overall elongation of the cloud shield along an axis from southwest to northeast (141120Z May NOAA enhanced infrared imagery).


TYPHOON YUNYA
BEST TRACK TC-05W
11 JUN- 17 JUN 91
MAX SFC WIND 105KT
MINIMUM SLP 938MB
E 105
110
115
120
125
130
135
140 E
N 30
25
20
15
10
N 5
L - 17/00Z
F - 13/00Z
TCFA
ABPW
12c
4a
55b
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TYPHOON YUNYA (05W)

I. HIGHLIGHTS

Typhoon Yunya, the first significant tropical cyclone of June, broke a nearly month-long lull in activity in the western North Pacific. Yunya was noteworthy because a ship transited through its center, providing a unique glimpse of the structure of a rapidly-developing midget typhoon. Its passage through central Luzon coincided with the massive eruption of Mount Pinatubo and subsequent evacuation of personnel from Clark AB.

II. TRACK AND INTENSITY

Yunya formed just east of Samar Island, Republic of the Philippines, in an area of low vertical wind shear associated with a col produced by a Tropical Upper Tropospheric Trough (TUTT). Unlike normal TUTT-induced tropical cyclone genesis which occurs in the region of strong upper-level divergence between the TUTT and the sub-equatorial ridge circulation to the southeast, Yunya's formation occurred southwest of the TUTT axis.

The broad disturbance which spawned Yunya was first discussed on the 110600Z Significant Tropical Weather Advisory. Between 111200Z and 121200Z, all surface reports within 100 nm (185 km) of the low-level circulation were less than 10 kt (5 m/sec). After a Tropical Cyclone Formation Alert was issued at 121500Z, the system began to rapidly develop. At 121730Z, a satellite analysis based on spiral band curvature estimated a maximum intensity of 30 kt (15 m/sec). Post analysis revealed a tiny central dense overcast (CDO) supporting 45 kt (23 m/sec). Then, at 121836Z the USNS **Spica** passed through the center of the system, and reported a central pressure of 989.5 mb with winds of 60 kt (30 m/sec). At 130000Z, JTWC issued its first warning on Yunya with an intensity of 45 kt (23 m/sec) was based on a conversion from observed minimum sea-level pressure to maximum sustained surface wind using the Atkinson-Holliday (1977) relationship. Post analysis determined the actual intensity was closer to 55 kt (28 m/sec).

Yunya reached minimal tropical storm intensity after existing for only 21 hours and minimal typhoon intensity in only 39 hours. In so doing, it did not exhibit the classic tropical cyclone development traits, but those of rapid initial development, small surface wind field, and peripheral surface pressure rises presumably associated with subsidence generated by a tiny annular outflow pattern aloft. These traits are found to be common with "midget typhoon" development. The fortuitous (for meteorologists) passage of the **USNS Spica** near the center of Yunya confirmed its midget size via the pressure trace shown in Figure 3-05-1. The wind observations reported by **Spica** indicate that the

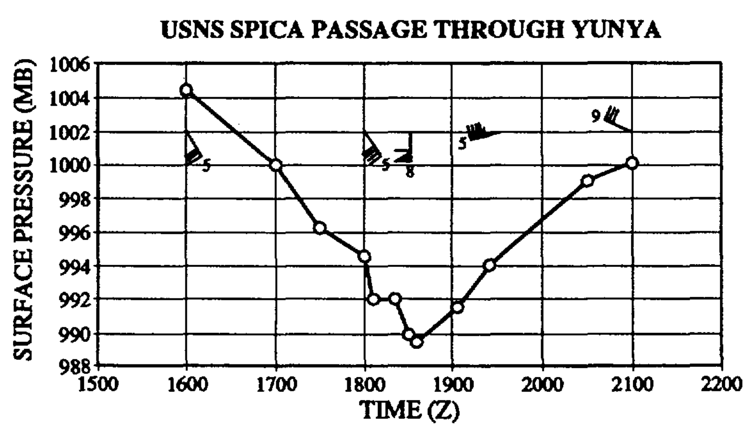


Figure 3-05-1. Time pressure cross-section reconstructed from data provided by the USNS **Spica**, which passed directly through the center of Yunya on the 12 of June.

area of winds greater than 30 kt (15 m/sec) was transited in a mere 5 hours. Since **Spica's** course and speed were reported as 286 degrees true at 16 kt (30 km/hr) for the duration of the transit, the associated 30 kt (15 m/sec) wind diameter for Yunya at this time was about 80 nm (150 km).

After moving northwestward for a day during its formation phase, Yunya then tracked west-northwestward toward central Luzon under the influence of the mid-level subtropical ridge. Yunya steadily intensified at a rate of 10 kt (5 m/sec) per 6 hours until 140600Z when it attained its peak intensity of 105 kt (55 m/sec) (Figure 3-05-2). Subsequently, strong north-northeasterly upper-level winds associated with an eastward building of the subtropical ridge circulation over Asia produced unfavorable vertical wind shear. As this shear (Figure 3-05-3) persisted, Yunya began to weaken even faster than it had intensified, having only minimal typhoon intensity as it made landfall just north of Dingalan Bay at 150000Z. Apparently, the midget size of the typhoon could not effectively buffer its core of convection from the shear. Yunya exited Luzon though the Lingayen Gulf as a weak tropical storm, and subsequently turned north toward a break in the subtropical ridge. The system continued to weaken due to strong vertical wind shear, grazing the southern tip of Taiwan as a tropical depression, and dissipating before it could complete full recurvature into the mid-latitude westerlies.

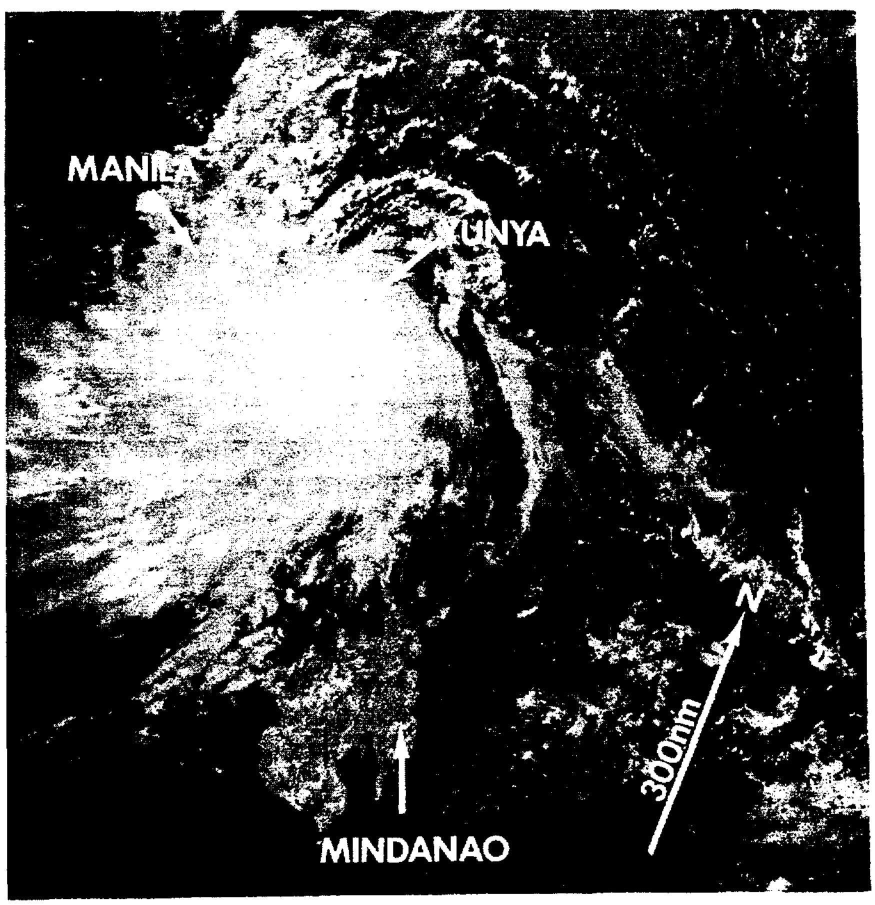


Figure 3-05-2. Yunya at peak intensity. Note the distortion of Yunya's cloud signature due to increasing upper-level north-northeasterly winds produced by a building subtropical ridge (140534Z June NOAA visual imagery).

III. FORECAST PERFORMANCE

The first two track forecasts issued by JTWC had Yunya moving in a northwestward direction toward a thin extension of the mid-level subtropical ridge, eventually grazing the northeast tip of Luzon (Figure 3-05-4). By the third warning however, JTWC correctly anticipated that Yunya's midget size

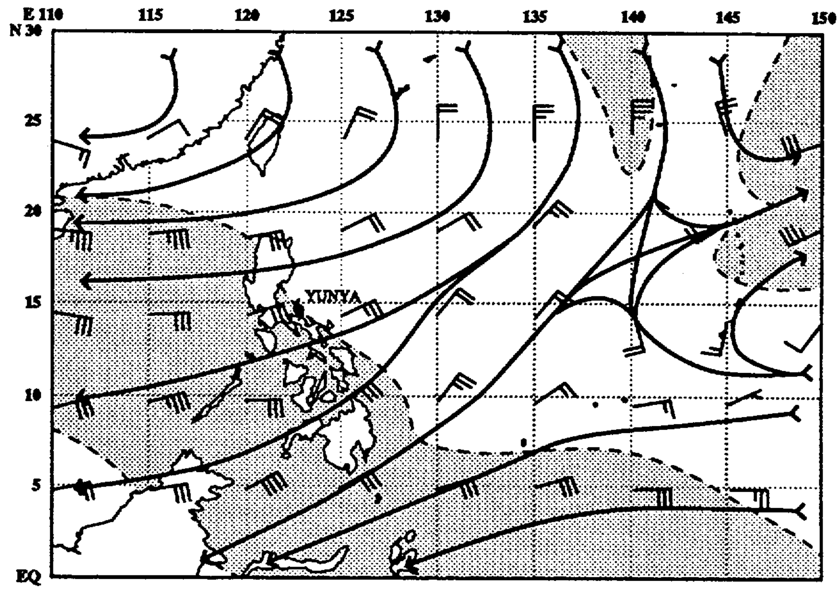


Figure 3-05-3. NOGAPS 200-mb analysis at 150000Z June showing an increased upper-level shear over Yunya. The JTWC hand-plotted/analyzed chart for this same this showed up to 40 kt (20 m/sec) 200-mb winds in the vicinity of Yunya. (Winds within the shaded area of the analysis are 30 kt (15 m/sec) or greater.)

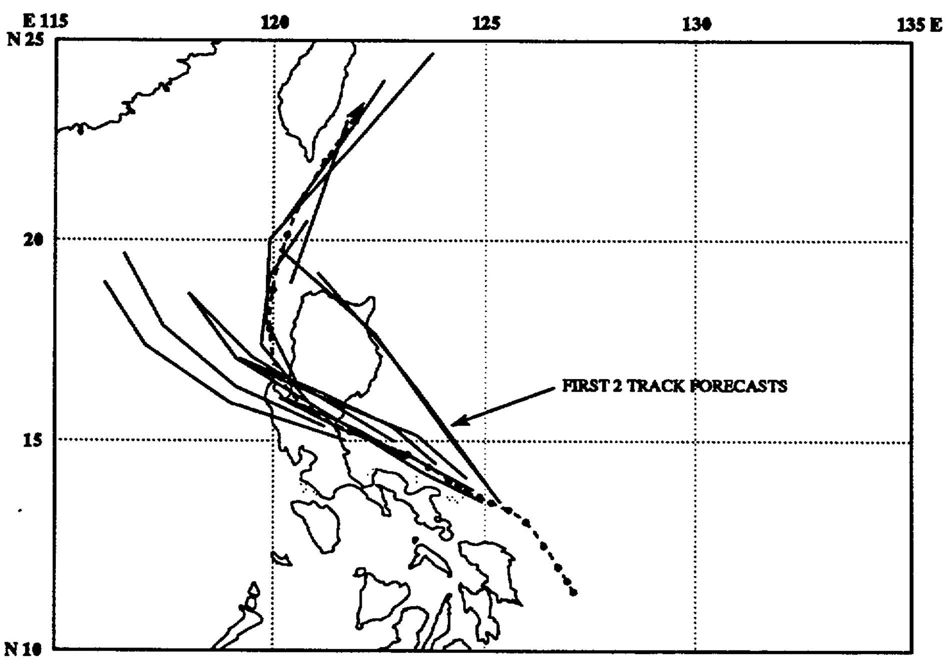


Figure 3-05-4. Graphic of all JTWC official forecasts issued for Yunya.

would prevent significant penetration into the thin ridge, and that Yunya would instead be steered around the periphery of the ridge, resulting in a track across central Luzon. After Yunya crossed Luzon, it turned toward the ridge axis sooner than anticipated, highlighting the sensitive and subtle interplay between tropical cyclone and weak ridge near the point of recurvature.

Figure 3-05-5 shows the objective forecast guidance that JTWC used to develop the 140000Z forecast, and Figure 3-05-6 shows the 48-hour NOGAPS 700-mb prognostic field associated with the mid-point of the 72-hour forecast period beginning at 140000Z. From these figures, it is evident that JTWC had to discount the track forecasts by the dynamical models NGPS and OTCM which tended to turn Yunya prematurely through the thin subtropical ridge. Forecasters placed more weight on climatology (CLIM), CSUM (statistical-dynamical) and FBAM (a steering-type dynamical aid) which provided better guidance, but which historically tend to be slow to forecast recurvature. It is interesting to note also that the Japanese Meteorological Agency Typhoon Model (JTYM) and the United Kingdom Meteorological Office Model (EGRR) also forecast Yunya through the thin ridge extension, suggesting that this problem is endemic to the current generation of vortex-tracking numerical models. With the midget typhoon, the model's inability to accurately describe the cyclone-ridge interaction may be a resolution problem.

Despite a slow speed bias, JTWC's forecasts of Yunya across Luzon provided key warning support which helped prompt DOD officials to evacuate the Clark and Subic areas in anticipation of the devastation to be caused by the Mount Pinatubo ash moistened and redirected by Yunya.

IV. IMPACT

Yunya made landfall in central Luzon near midday on 15 June, and the associated heavy rainfall caused flooding that washed away bridges and left one person dead. However, this direct impact of Yunya was relatively minimal compared to its subsequent influence on the massive cloud of ash produced by the eruption of Mount Pinatubo on the same day. As Yunya crossed central Luzon, its deep cyclonic circulation redistributed the ash, that normally would have been carried out over the South China Sea, over land. This greatly aggravated the impact of the water-laden ash fall-out on Clark AB and at the Subic Bay/Cubi Pt naval complex, resulting in the downing of power lines and the collapse of most flat-roofed buildings due to overloading.

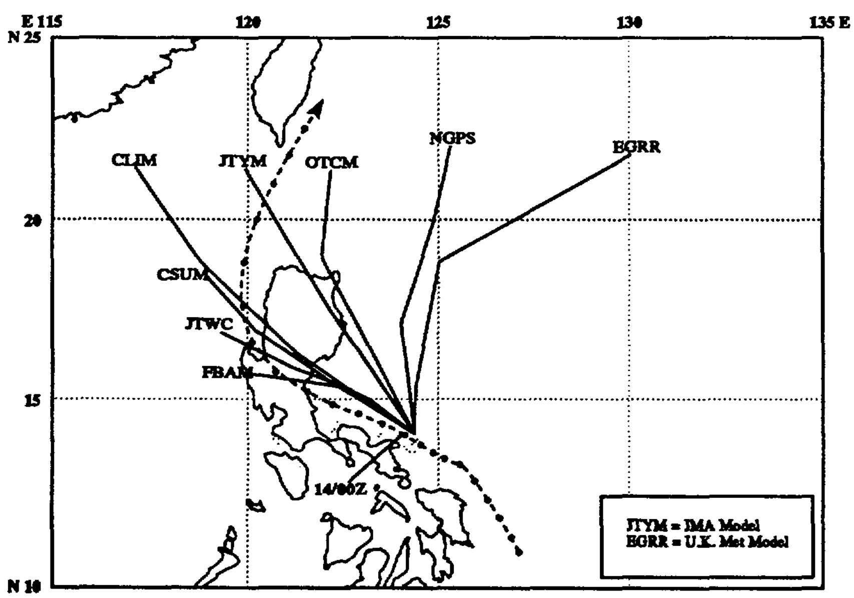


Figure 3-05-5. Graphic of JTWC official forecast and the associated objective forecast aids valid at 140000Z June.

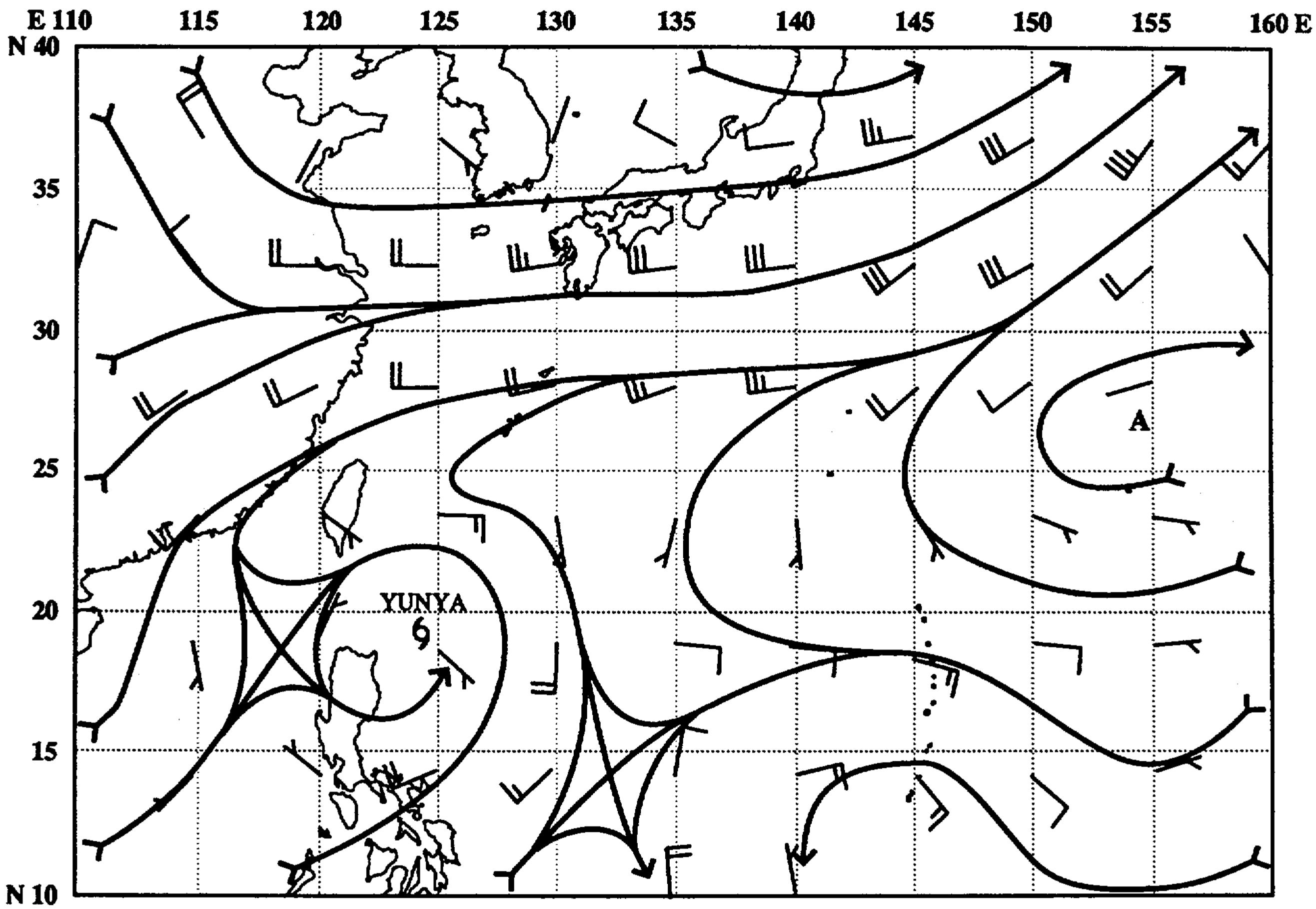
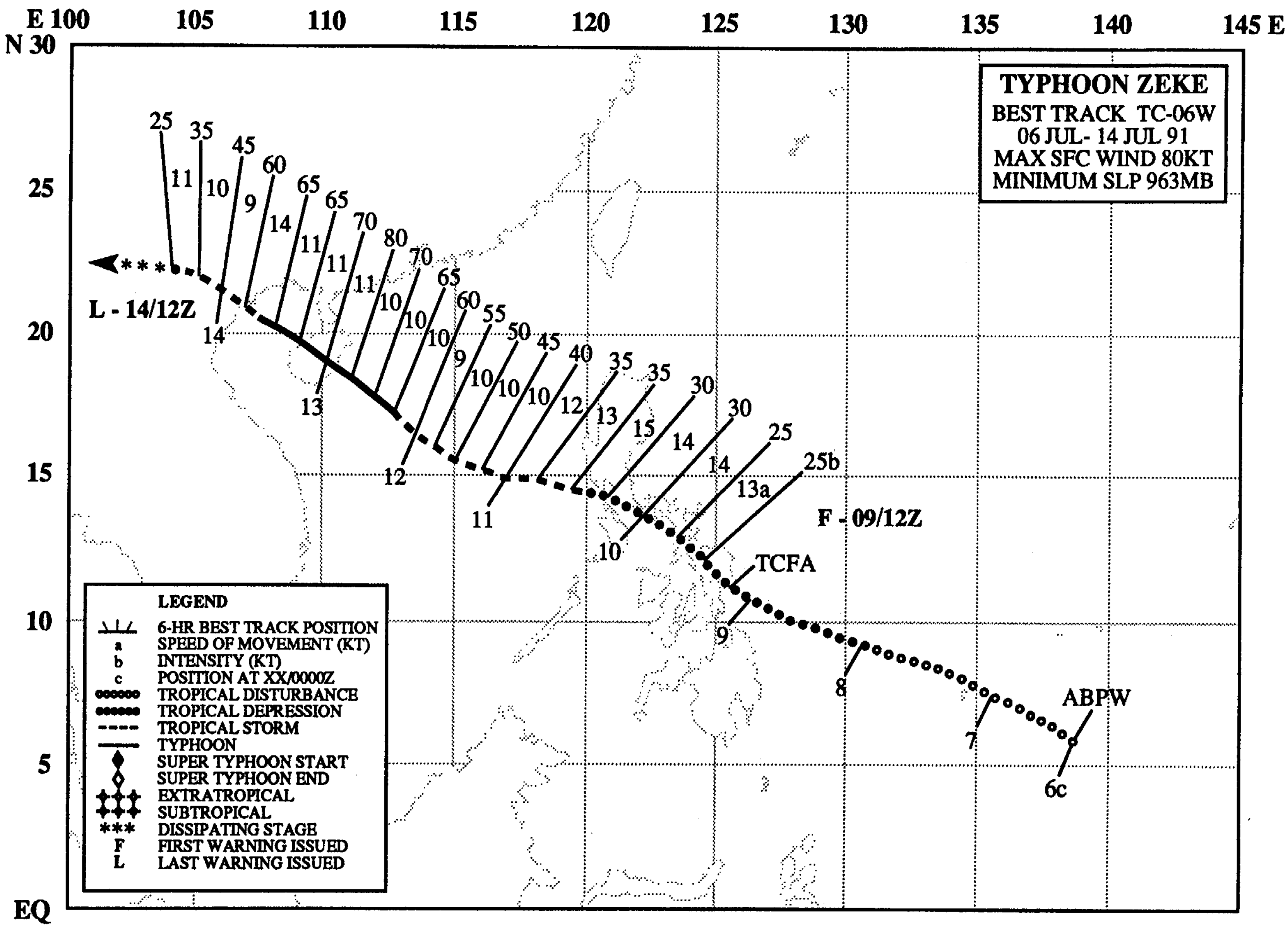


Figure 3-05-6. NOGAPS 700-mb 48-hour prognostic field valid at 151200Z, which is the midpoint of the forecast period beginning at 140000Z.



TYPHOON ZEKE
BEST TRACK TC-06W
06 JUL- 14 JUL 91
MAX SFC WIND 80KT
MINIMUM SLP 963MB
E 100
105
110
115
120
125
130
135
140
145 E
N 30
25
20
15
10
5
EQ
L - 14/12Z
F - 09/12Z
TCFA
ABPW
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TYPHOON ZEKE (06W)

I. HIGHLIGHTS

Starting in the Philippine Sea, Typhoon Zeke (06W) made landfall three times before it dissipated over the mountains of northern Vietnam. Zeke was the first tropical cyclone to develop during the month of July, and initiated a period of nearly continuous warning status on at least one tropical cyclone in the Northwest Pacific through early December.

II. TRACK AND INTENSITY

For the most part, the subtropical ridge provided the primary steering for Zeke's persistent track to the west-northwest. The slight northward jog across the Philippine Islands from the basic track appears related to a surge in the southwesterly monsoonal flow over the South China Sea.

Zeke developed from a tropical disturbance in the monsoon trough southwest of Guam. Increased convection associated with the disturbance was first mentioned on the 060600Z Significant Tropical Weather Advisory. When the cyclonic circulation became evident on animated satellite imagery, a Tropical Cyclone Formation Alert was issued at 090400Z. The first warning on Tropical Depression 06W followed at 091200Z as the deep convection steadily increased around the cyclone's center. Zeke crossed the Republic of the Philippines as a depression and was upgraded to a tropical storm once it moved over open water in the South China Sea on 10 July. Synoptic reports from ships in the South China Sea revealed a highly asymmetric wind distribution around the cyclone center. The radius of 30 kt (15 m/sec) winds extended over 250 nm (465 km) southeast of the center, but less than 100 nm (185 km) to the northwest. This asymmetry appeared related to an adjustment of the monsoon southwesterlies due to the presence of the tropical cyclone, producing a cyclone structure similar to a large monsoon depression. Zeke reached its maximum intensity of 80 kt (40 m/sec) shortly before making landfall on Hainan Dao, but weakened very little crossing the island (Figure 3-06-1). It struck the coast of northern Vietnam, passing close to Hanoi. The final warning was issued at 141200Z as Zeke dissipated inland.

III. FORECAST PERFORMANCE

Although Zeke's final best track was nearly a straight line, the actual forecasts called for recurvature just east of Hainan Dao (Figure 3-06-2). Zeke was expected to turn northward near Hainan based on the NOGAPS prognostic series, which indicated that the subtropical ridge would break down near 110°E longitude. Rather than breaking down, the ridge north of the system strengthened and built westward as the long wave trough near 110°E retrograded allowing the high located near Okinawa to move westward towards Taiwan. Once forecasters recognized the adjustment of the ridge to the north, which prevented Zeke from moving directly northward, the forecasts reverted back to the straight-runner scenario.

IV. IMPACT

Despite passage close by the major population centers of Manila and Hanoi, Zeke's impact appeared to be negligible. No reports of significant damage were received, but damage to agriculture was probably high in Hainan Dao and northern Vietnam.

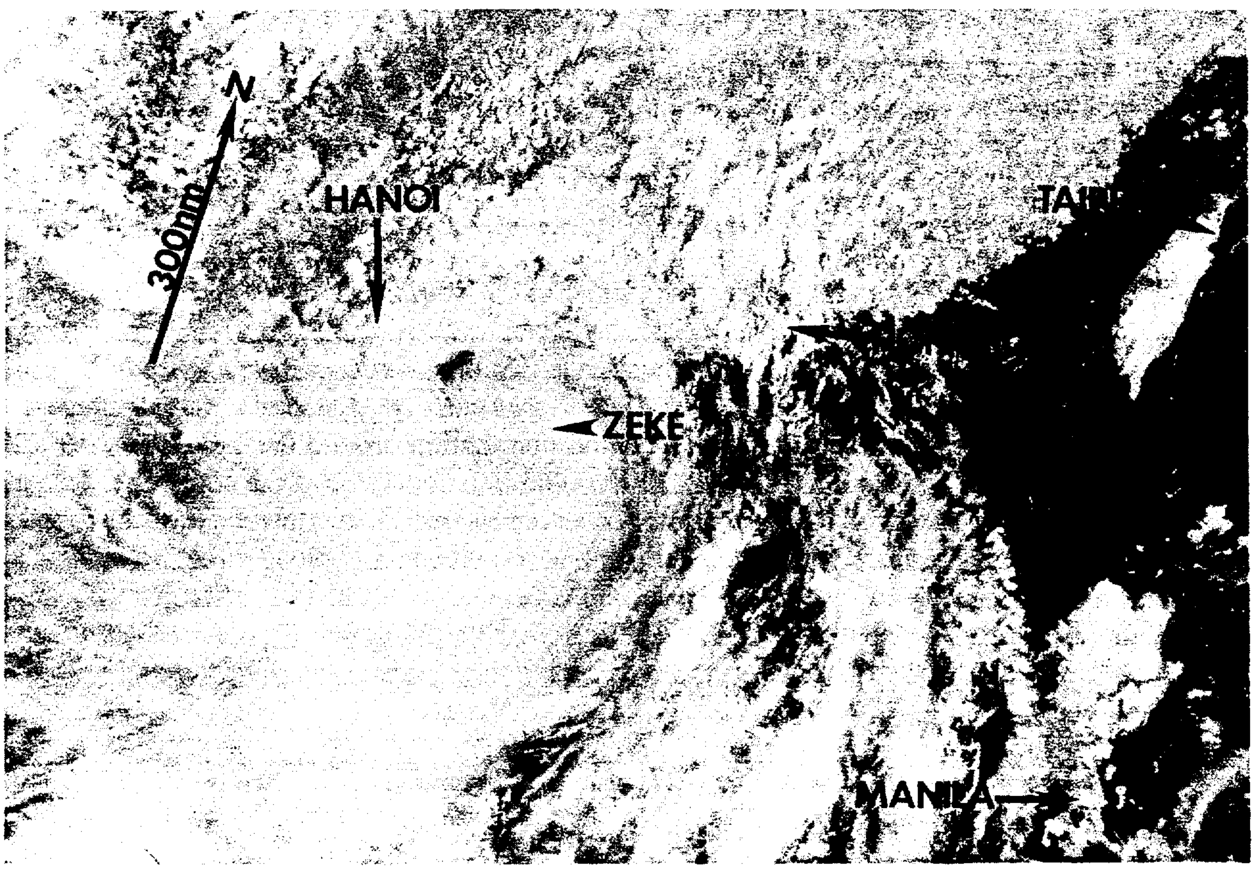


Figure 3-06-1. After crossing Hainan Dao, Typhoon Zeke retains 70 percent of its eyewall as it enters the Gulf of Tonkin (130644Z July NOAA visual imagery).

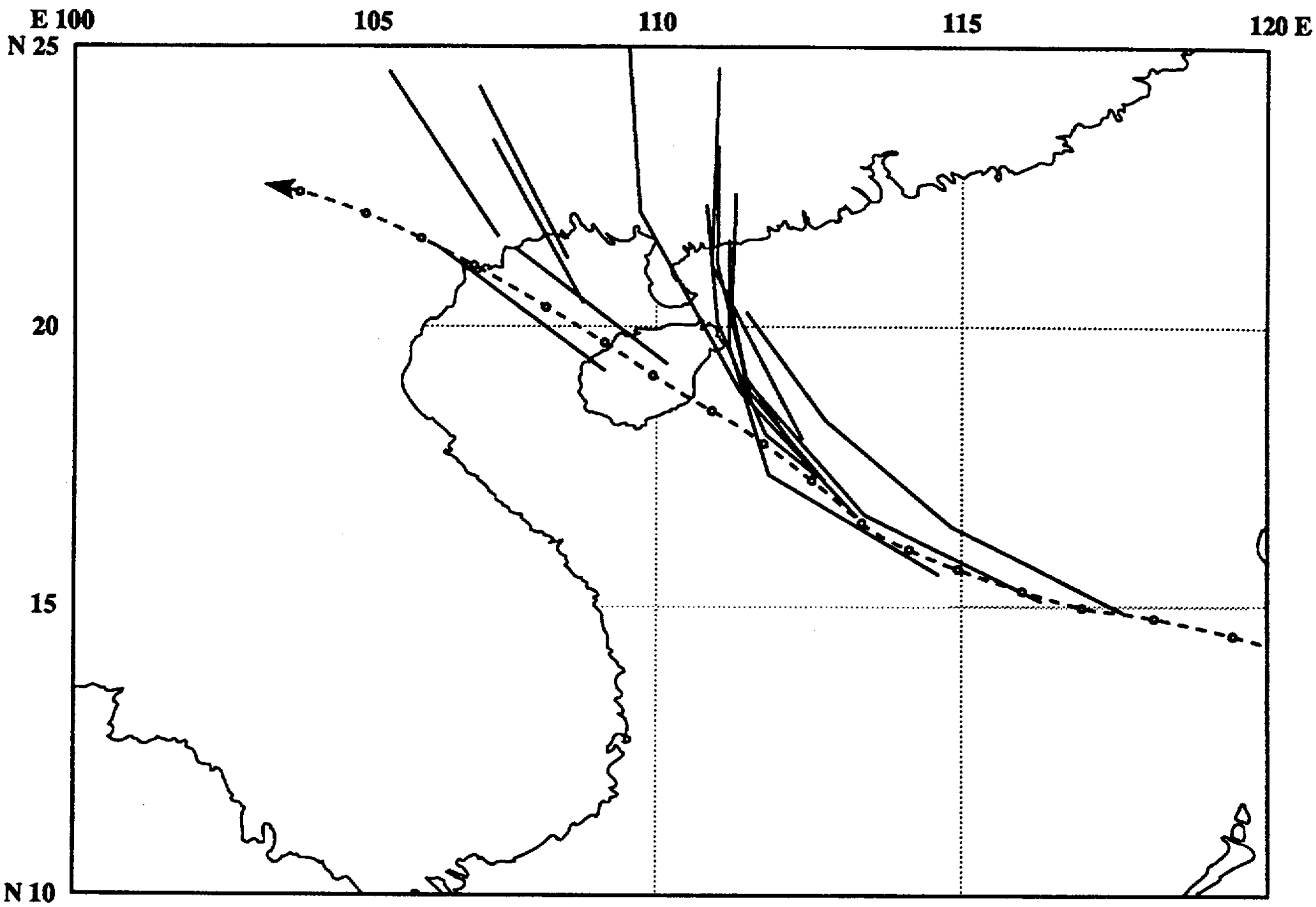
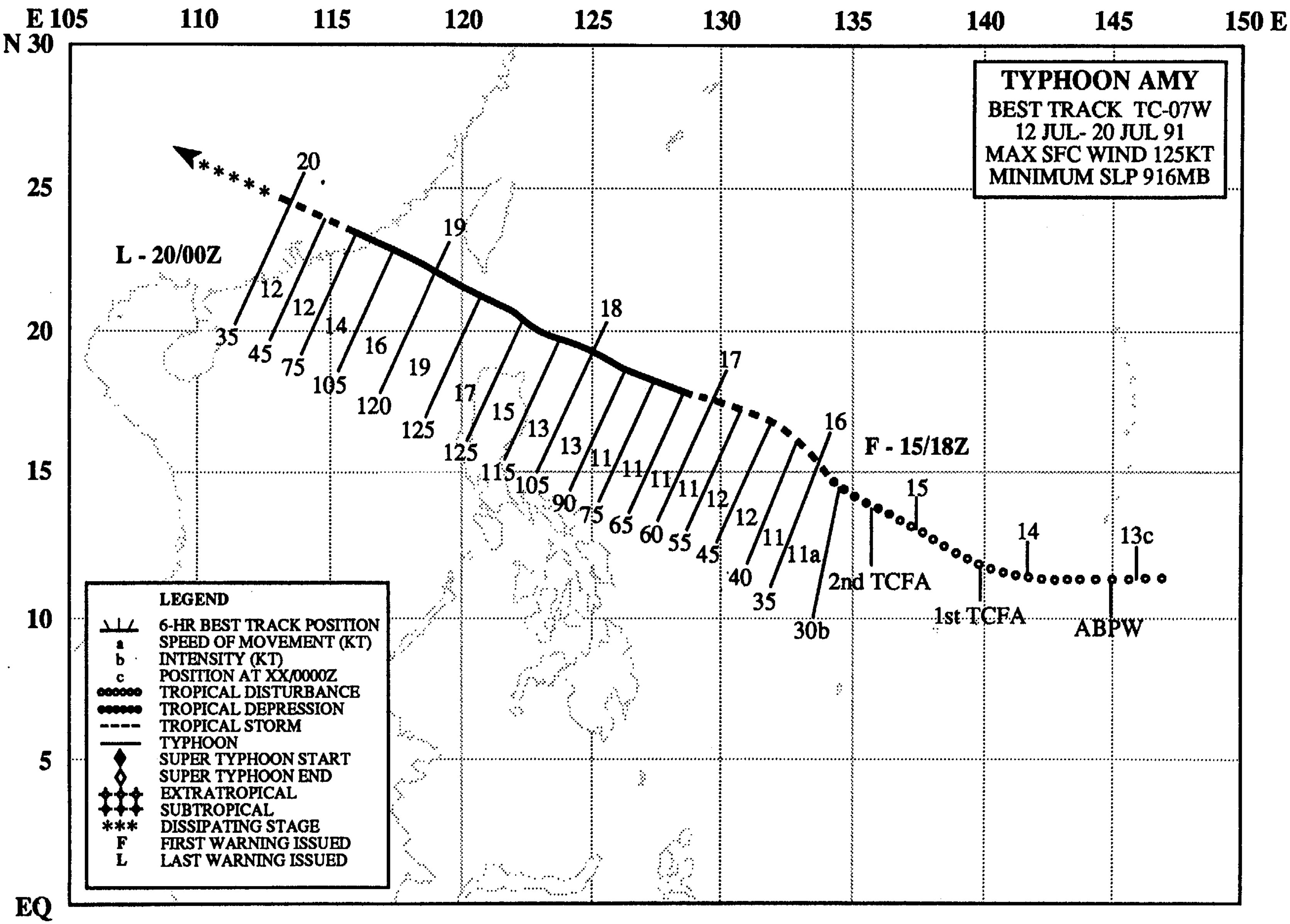


Figure 3-06-2. A comparison of JTWC forecasts issued after 101800Z July to the final best track. Recurvature was anticipated near 110°E longitude, but did not occur.


TYPHOON AMY
BEST TRACK TC-07W
12 JUL- 20 JUL 91
MAX SFC WIND 125KT
MINIMUM SLP 916MB
E 105
110
115
120
125
130
135
140
145
150 E
N 30
25
20
15
10
5
EQ
L - 20/00Z
F - 15/18Z
2nd TCFA
1st TCFA
ABPW
LEGEND
6-HR BEST TRACK POSITION
SPEED OF MOVEMENT (KT)
INTENSITY (KT)
POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
FIRST WARNING ISSUED
LAST WARNING ISSUED

TYPHOON AMY (07W)

I. HIGHLIGHTS

The second of five tropical cyclones to form in July, Amy followed a west-northwesterly track that paralleled the one taken a week earlier by Typhoon Zeke (06W). Near Taiwan, the typhoon caused the loss of the freighter, **Blue River**, with its entire crew, and then became the deadliest typhoon to strike China this year.

II. TRACK AND INTENSITY

Amy, like typhoon Zeke (06W), took a straight-line west-northwestward track and remained south of the subtropical ridge axis. There was a small stair-step, or jog northwestward, on 16 July for about 18 hours as a mid-tropospheric shortwave trough passed by to the north. This shortwave temporarily weakened the ridge, and allowed Amy to gain latitude. Strong subsidence immediately behind the passing shortwave strengthened the subtropical ridge, once again producing a more easterly steering flow.

The tropical disturbance that became Amy was first mentioned in the Significant Tropical Weather Advisory at 130600Z after 18 hours of persistent convection. Increased convection, 2-mb pressure falls in a 24-hour period at Yap (WMO 91413), and the indication of little vertical wind shear led to the initial Tropical Cyclone Formation Alert at 141000Z. Although the overall cloud organization remained poor, deep convection persisted and a second alert followed at 151000Z. After the initial warning at 151800Z, Amy intensified at a rate of 5-10 kt (3 to 5 m/sec) every 6 hours. On the evening of 17 July, Amy began intensifying more rapidly, reaching a peak intensity of 125 kt (65 m/sec) in the Luzon Strait (Figure 3-07-1). The weakening trend began late on 18 July as the outflow became more restricted to the northwest and the typhoon approached the coast of mainland China (Figure 3-07-2). Upon making landfall, the system dissipated rapidly over the mountains in southeastern China. The final warning was issued at 200000Z.

III. FORECAST PERFORMANCE

Although the overall track forecast errors were below average there were some flaws: 1) the track acceleration in the Taiwan Straits was not anticipated or handled well by the dynamic models; 2) the forecast for the observed strong intensification was handled as a low probability alternate scenario until it actually was observed; and, 3) the unusual extension of gale and storm force winds far to the northeast of the typhoon was not anticipated. For example, Amy was at peak intensity in the Luzon Strait when the **USNS Hassayampa** reported 77 kt (40 m/sec) winds at a position 315 nm (585 km) to the northeast.

IV. IMPACT

Hengchun (WMO 46752) located on the southern tip of Taiwan reported sustained winds of 66 kt (33 m/sec) with gusts of 130 kt (65 m/sec) and an unusually high peak wind gust of 150 kt (75 m/sec) at 182000Z, some 30 nm (55 km) from Amy's center. The 16,000 ton freighter, **Blue River**, with 31 persons onboard, capsized and sank near the Pescadores Islands west of Taiwan. There were no survivors. On 19 July, Amy plowed into southeastern China, 99 people were killed, at least 5000 injured and over 15,000 homes destroyed.

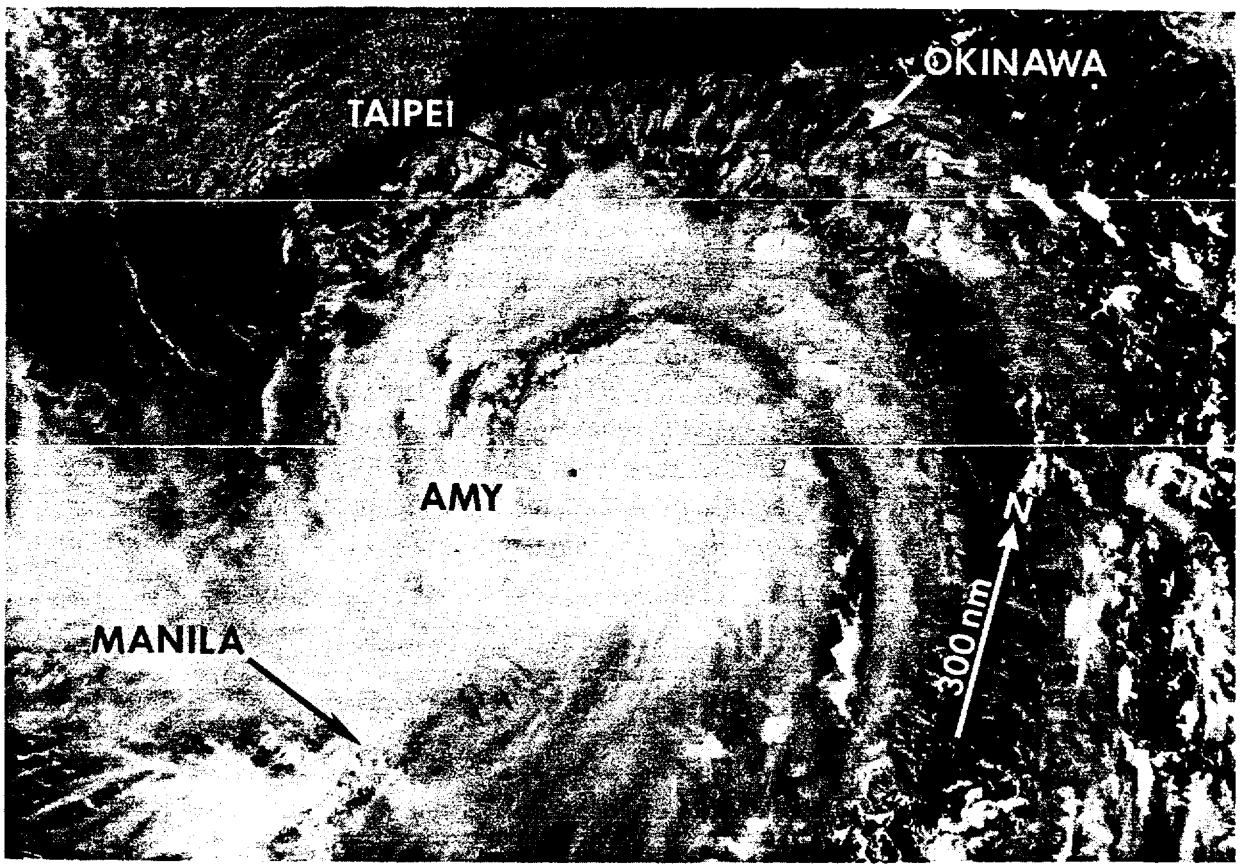


Figure 3-07-1. Amy, with an intensity near 115 kt (60 m/sec), passes through the Luzon Strait with a small 10 nm (20 km) diameter eye (180546Z July NOAA visual imagery).

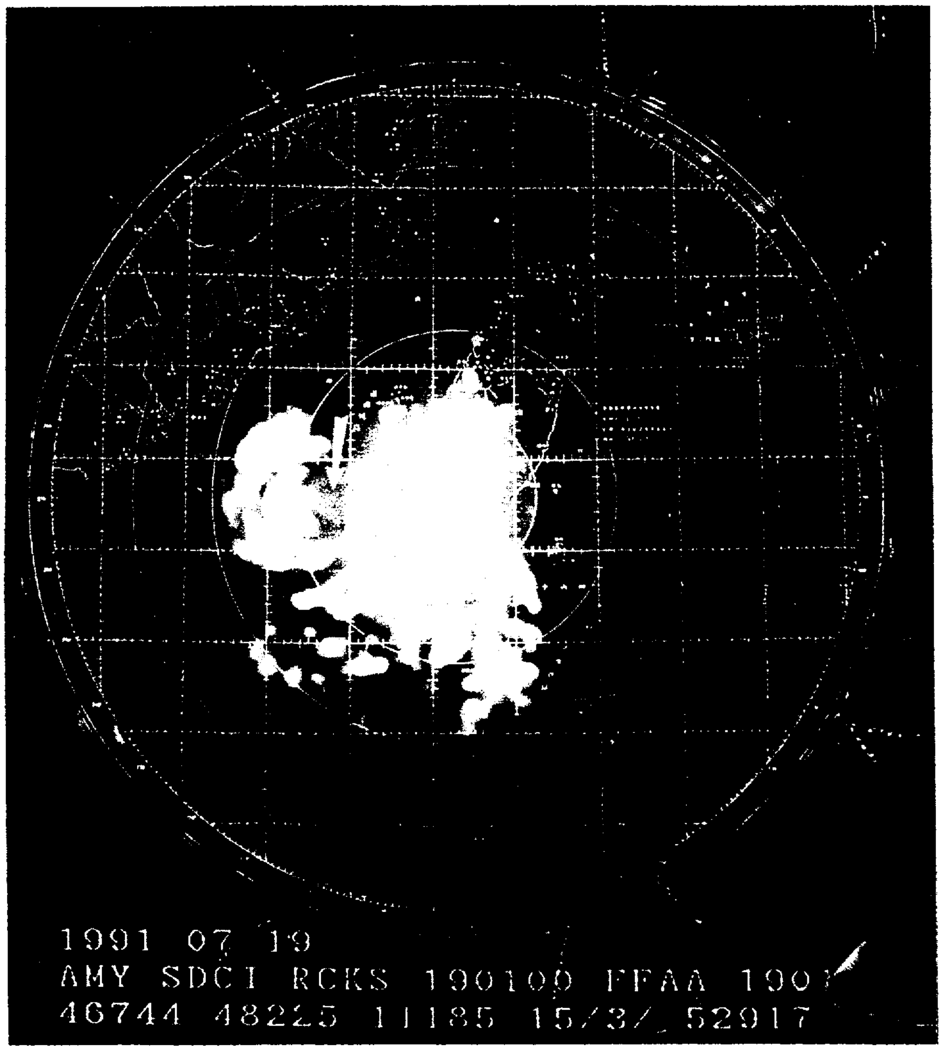
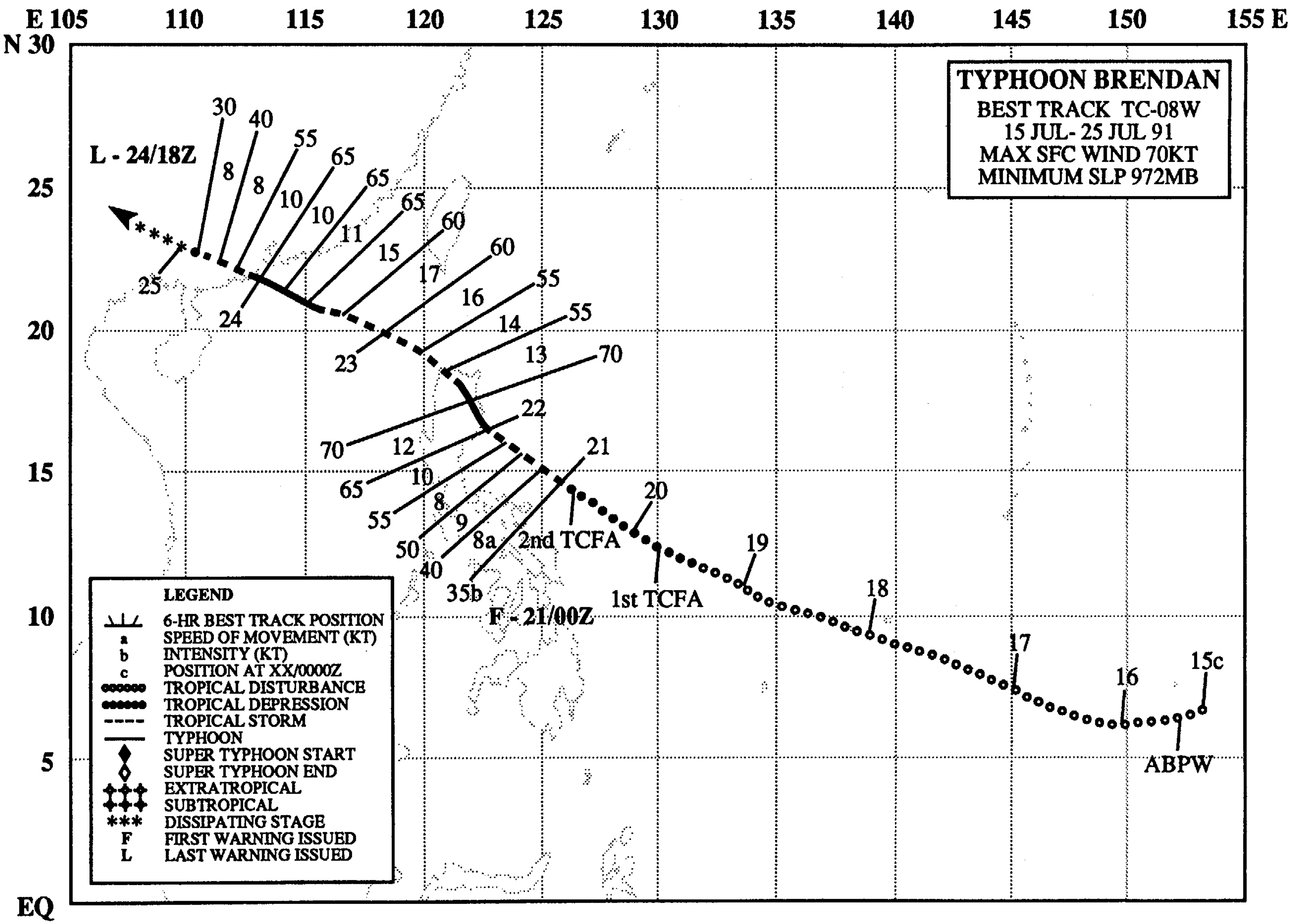


Figure 3-07-2. The radar at Kaohsiung (WMO 46744) at 190100Z July reveals tightly curved concentric rainbands surrounding Amy's eye (Photograph courtesy of the Central Weather Bureau, Taipei, Taiwan).



TYPHOON BRENDAN
BEST TRACK TC-08W
15 JUL- 25 JUL 91
MAX SFC WIND 70KT
MINIMUM SLP 972MB
E 105
110
115
120
125
130
135
140
145
150
155 E
N 30
25
20
15
10
5
EQ
L - 24/18Z
F - 21/00Z
1st TCFA
2nd TCFA
ABPW
15c
16
17
18
19
20
21
22
23
24
25
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TYPHOON BRENDAN (08W)

I. HIGHLIGHTS

The third tropical cyclone of July, Brendan was the third straight-runner in a row. Torrential rains associated with the tropical cyclone's passage across northern Luzon unleashed lahars or avalanches of volcanic debris, mud and boulders in the valleys near Mount Pinatubo. The forecast models performed very well throughout the duration of this tropical cyclone, and JTWC's forecast errors were below average.

II. TRACK AND INTENSITY

A weak surface circulation developed 70 nm (130 km) south-southeast of Chuuk in the central Caroline Islands on 15 July. The cloud system tracked generally west-northwestward for several days until it moved into an area of increased upper level divergence in the central Philippine Sea on the nineteenth. At 191800Z, JTWC issued the first Tropical Cyclone Formation Alert. At that time the system was located approximately 230 nm (425 km) east of the Philippine island of Samar. Due to the extreme diurnal fluctuations in the system's convection which delayed intensification, JTWC re-issued the alert at 201800Z. The first visual satellite imagery available later that morning showed significant low-level cloud lines north of an organized surface circulation. This level of organization coupled with a low shear environment and warm sea surface temperatures, prompted JTWC to issue the first 72-hour tropical cyclone warning on Tropical Depression 08W at 210000Z.

Tropical Depression 08W was upgraded to Tropical Storm Brendan on the 210600Z warning, based on a Dvorak intensity estimate of 35 kt (18 m/sec). Intensification continued over the next 36 hours, and the system reached marginal typhoon intensity before making landfall over northern Luzon. Initially it appeared that the system would track more northward along the coast to the east of the Sierra Madre mountain range rather than over the mountains. However, after making landfall, Brendan continued to track northwestward across the mountains and emerged at tropical storm intensity on the northwestern coast of Luzon at 221200Z (Figure 3-08-1). As Tropical Storm Brendan accelerated to the west-northwest away from northern Luzon, it began to reintensify, attaining typhoon intensity for a second time at 230000Z (Figure 3-08-2) in the South China Sea. The peak intensity of 75 kt (39 m/sec) occurred at 231200Z, approximately 12 hours before the typhoon made landfall over southeastern China approximately 30 nm (55 km) southwest of Macau. After making landfall, Brendan continued to move northwestward and weaken. JTWC issued the final warning on this tropical cyclone at 241800Z, as it was dissipating over land.

III. FORECAST PERFORMANCE

JTWC performed well with mean forecast errors of 94, 127 and 158 nm at 24 , 48 and 72 hours respectively. In comparison, as a measure of skill the climatology-persistence model CLIPER had errors of 113, 238 and 370 nm for the same time periods. Initially, JTWC forecasts were to the south of the actual track.

IV. IMPACT

Brendan had a significant impact on both the Philippines and China. In the Philippines, torrential rainfall combined with volcanic debris from Mt. Pinatubo's June eruption to produce mudflows (lahars) up to 15 feet high in the river valleys near the volcano. Three fatalities were reported. In addition, 1400 homes were destroyed and 10,000 people evacuated. Peripheral winds and rain from the typhoon brushed across Hong Kong causing 16 minor injuries due to flying debris. Waglan Island (WMO 45009) to the south reported winds of 55 kt (29 m/sec) gusting to 80 kt (41 m/sec) while Hong Kong's Kai Tak airport (WMO 45007), which was more sheltered, recorded winds of 35 kt (18 m/sec) gusting to 55 kt (28 m/sec). However, China was greatly impacted by Brendan, which exacerbated the flooding situation already present from abnormally high spring and early summer rainfall. At least 100 fatalities were attributed to the typhoon as it moved inland.

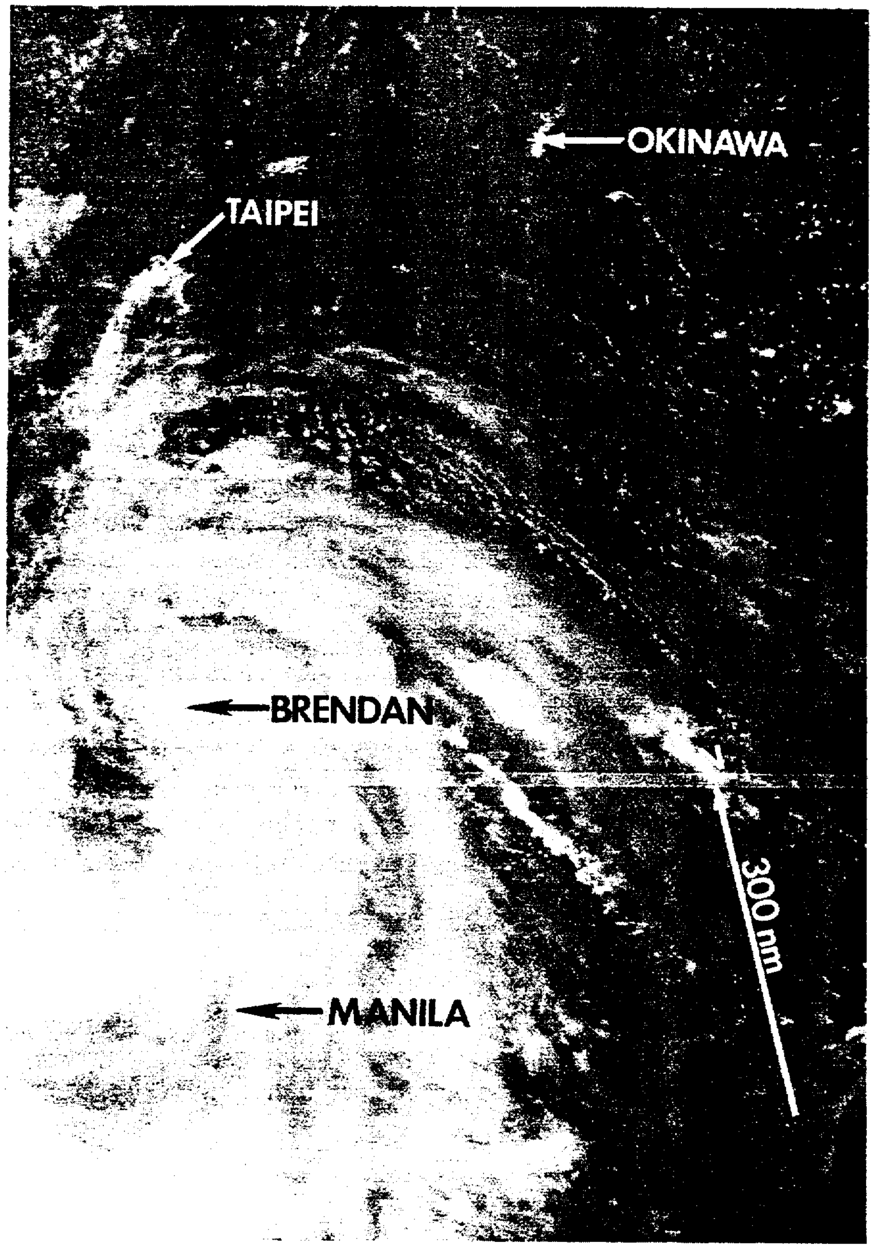


Figure 3-08-1. Brendan at tropical storm intensity shortly after moving off Luzon into the South China Sea (221253Z July DMSP infrared imagery).

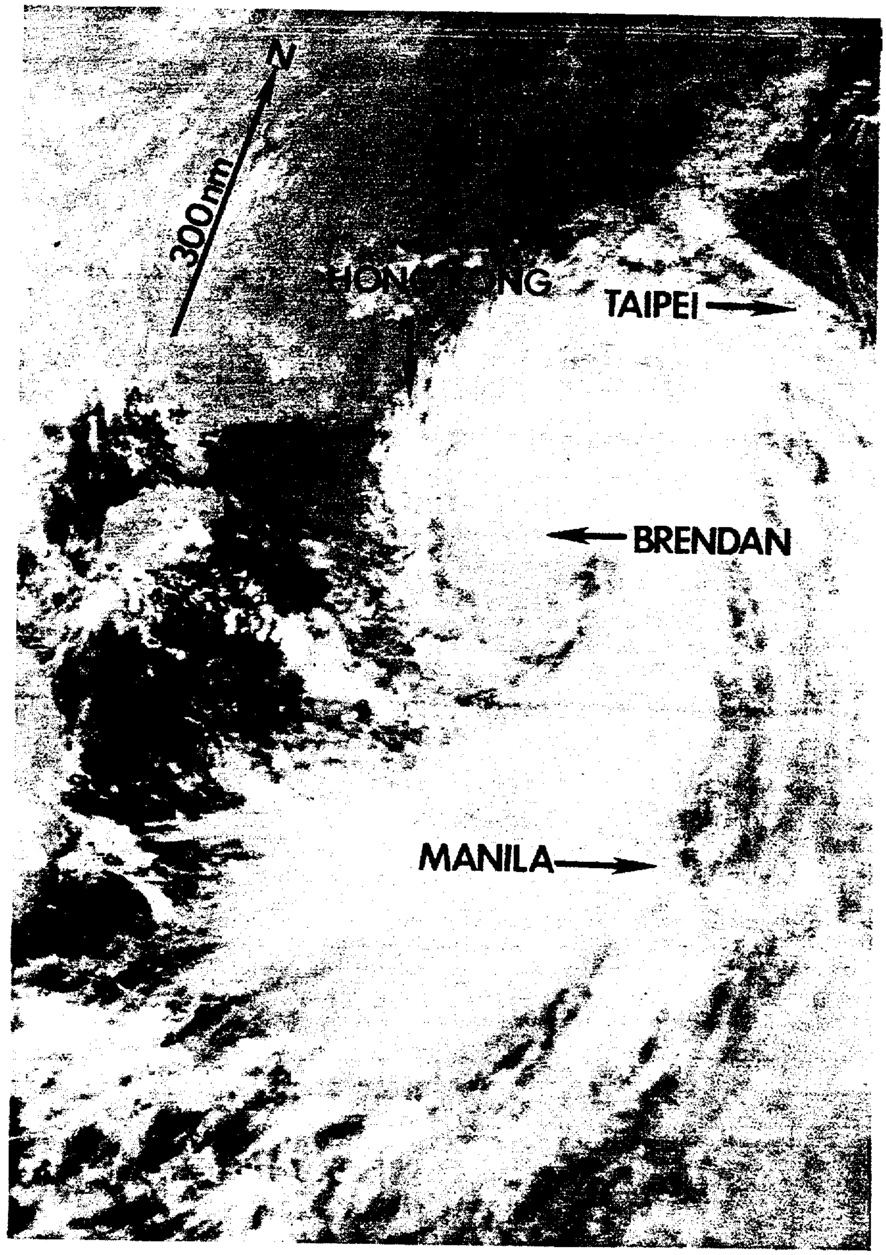
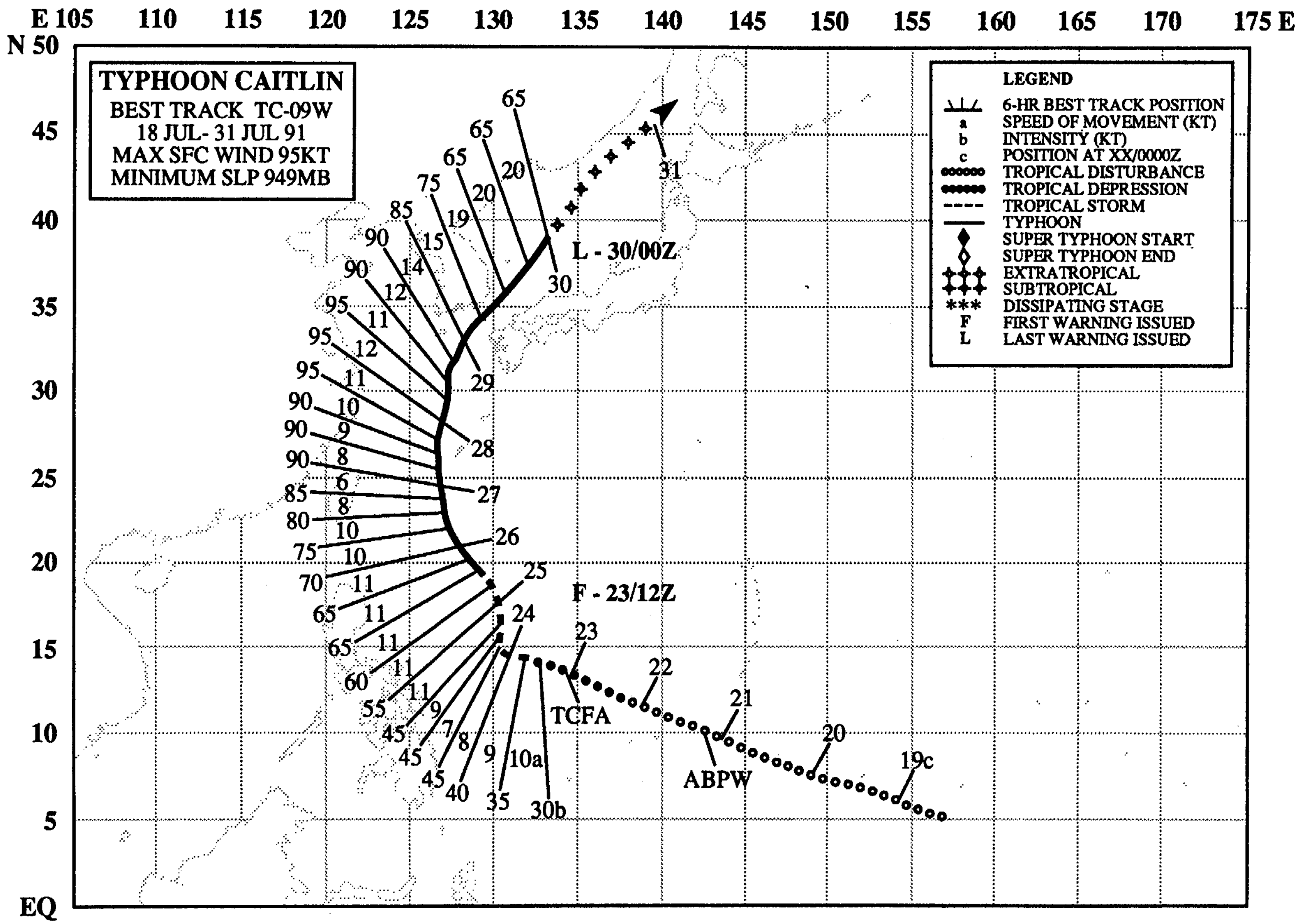


Figure 3-08-2. Brendan just after being upgraded to typhoon status in the South China Sea (230133Z July DMSP visual imagery).



TYPHOON CAITLIN
BEST TRACK TC-09W
18 JUL- 31 JUL 91
MAX SFC WIND 95KT
MINIMUM SLP 949MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
L - 30/00Z
F - 23/12Z
TCFA
ABPW
E 105
110
115
120
125
130
135
140
145
150
155
160
165
170
175 E
N 50
45
40
35
30
25
20
15
10
5
EQ

TYPHOON CAITLIN (09W)

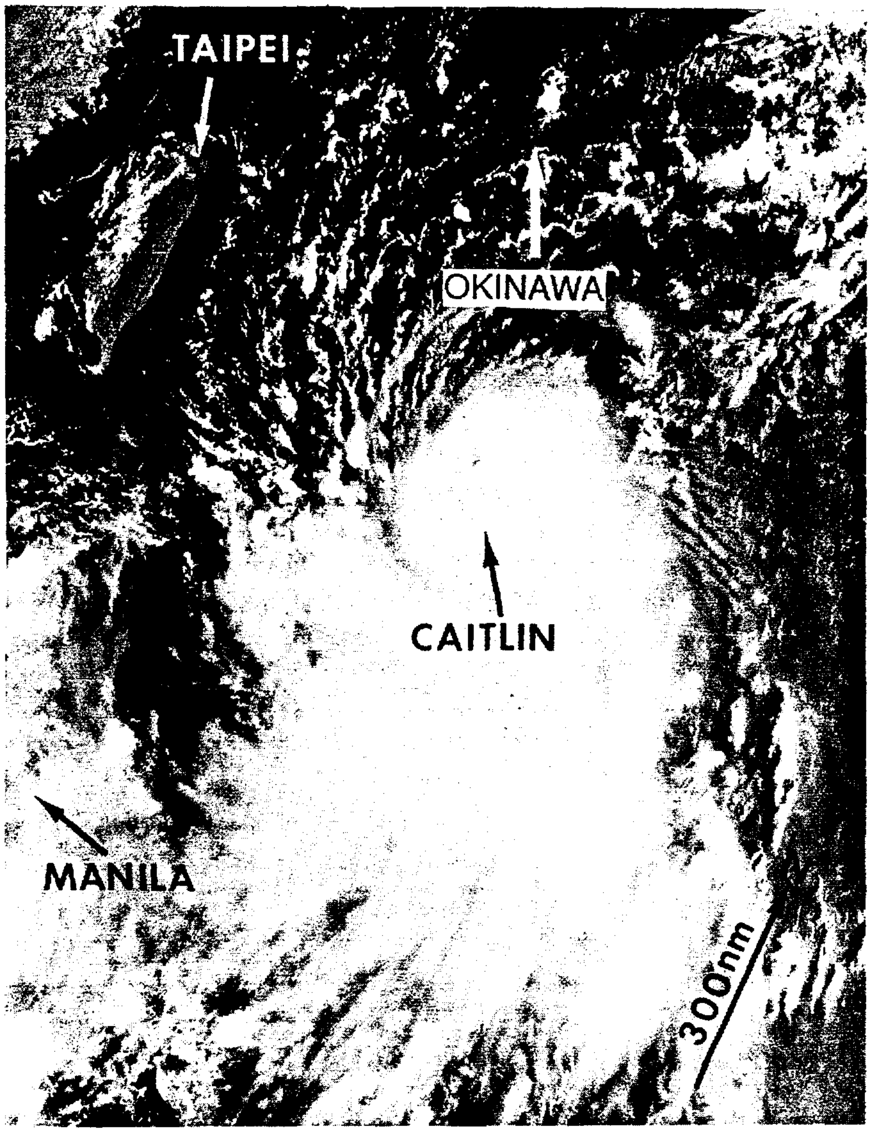


Figure 3-09-1. Caitlin has a cloud filled eye. To the north, the first line of enhanced cumulus cloud bands associated with the typhoon move across Okinawa (260028Z July DMSP visual imagery).

I. HIGHLIGHTS

After a succession of three straight-running July typhoons [Zeke (06W), Amy (07W), and Brendan(08W)], Caitlin became the first cyclone of the season to threaten Japan and Korea. Its north-oriented track was predicted by the NOGAPS model, and appeared to demonstrate the value of a newly implemented tropical cyclone bogus routine implemented at Fleet Numerical Oceanographic Center (FNOC). Much-needed rain fell on drought-stricken Okinawa as Caitlin passed west of the island.

II. TRACK AND INTENSITY

In mid-July, Caitlin developed from a disturbance in the eastern portion of the monsoon trough which extended south of Pohnpei in the eastern Caroline Islands. The disturbance moved west-northwestward, and was initially described on the 200600Z July Significant Tropical Weather Advisory as a low-level circulation with much of the deep convection displaced west of the center. On 22 July, upper-level wind shear diminished near the circulation center. Based on pressure falls of 1 to 2 mb per day at Yap (WMO 91413), and increased convective activity, a Tropical Cyclone Formation Alert was issued at 230500Z. The first warning on Tropical Depression 09W followed at 231200Z when a significant increase in convection indicated that continued intensification was likely to occur. Caitlin became a tropical storm at 240000Z.

Caitlin tracked west-northwestward until 24 July, when the subtropical ridge weakened near 130°E and allowed the tropical storm to make a sharp northward turn. For the next four days, it moved in a generally north-northwestward direction and slowly intensified. The development of an irregular, cloud-filled eye prompted an upgrade to typhoon intensity at 251200Z (Figure 3-09-1). At 271535Z, the center of the eye passed 60 nm (111 km) west of Kadena AB and Caitlin attained a peak intensity of

95 kt (49 m/sec) less than three hours later at 271800Z. After passing Okinawa, the typhoon tracked north-northeastward around the periphery of a broad mid-tropospheric subtropical ridge. On 29 July, Caitlin took a more northeastward track, accelerated through the Korea Strait, and gradually transitioned into a typhoon force extratropical low as it moved into the Sea of Japan. The final warning was issued at 300000Z when satellite imagery indicated the system had lost most of its tropical characteristics.

III. FORECAST PERFORMANCE

Initially, JTWC predicted Caitlin would follow a west-northwest track similar to the paths taken earlier by the three preceding typhoons. Of the suite of available computer forecast guidance, only the NOGAPS model indicated the cyclone would cease moving west-northwestward and assume instead a north-oriented track. This NOGAPS forecast was the subject of much speculation at the JTWC because it was uncertain if a recently implemented tropical cyclone bogus program was producing spurious output from the model. A post analysis evaluation of the bogus program, where bogus rawinsonde data derived from tropical cyclone characteristics are inserted into the NOGAPS model at the location of the tropical cyclone, showed that the program significantly improved model output in the tropics during 1991. After Caitlin made its abrupt northward turn on 24 July, JTWC forecasters responded by shifting the forecast from west-northwest to a northward track, which was consistent with the NOGAPS prognosis. As shown in Figure 3-09-2, official forecasts starting at 241800Z flip-flopped, or "windshield wiped" from northwest, to north, then north-northwest, before settling on a consistent northward track west of Okinawa. Forecast errors during this period were small,

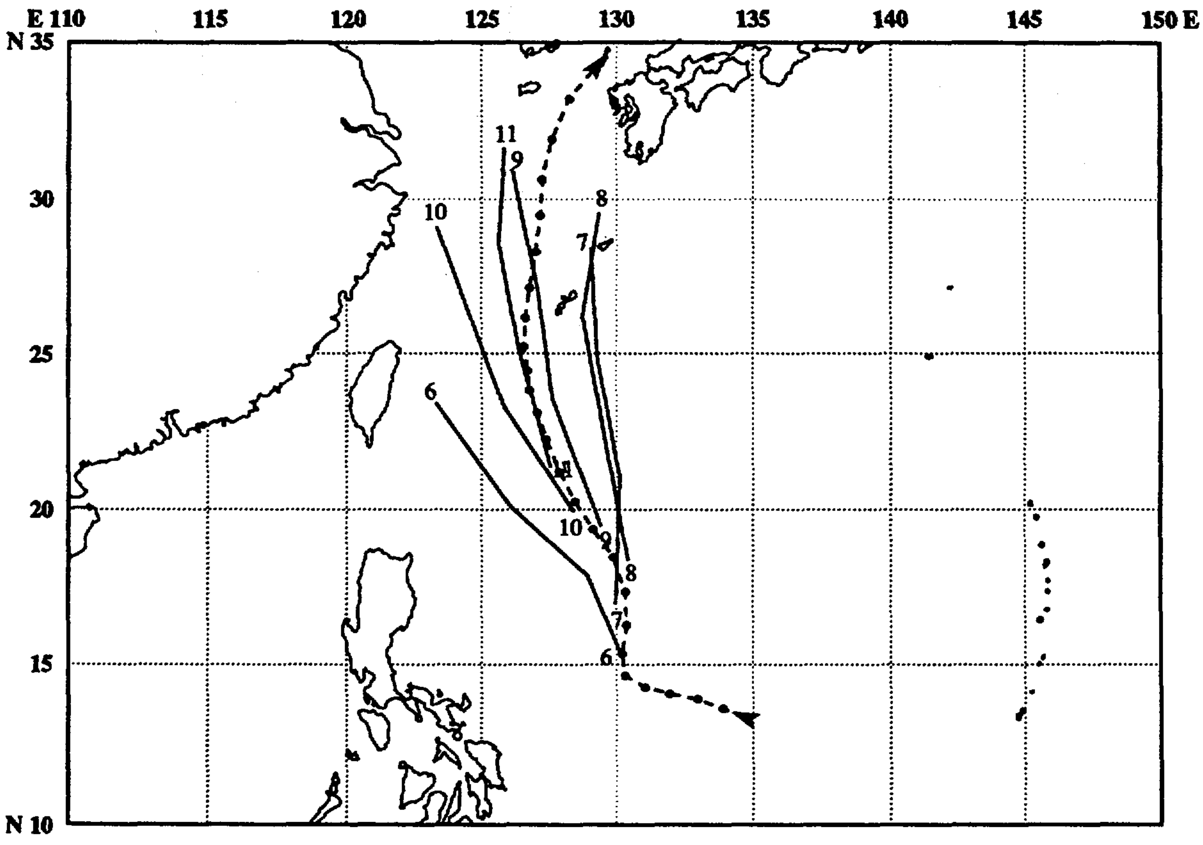


Figure 3-09-2. Comparison of JTWC forecasts issued from 241800Z to 260000Z July to the best track illustrates a significant change in JTWC track forecasts beginning at 250000Z (warning #7), and that a large degree of directional variability occurred in the subsequent track forecasts.

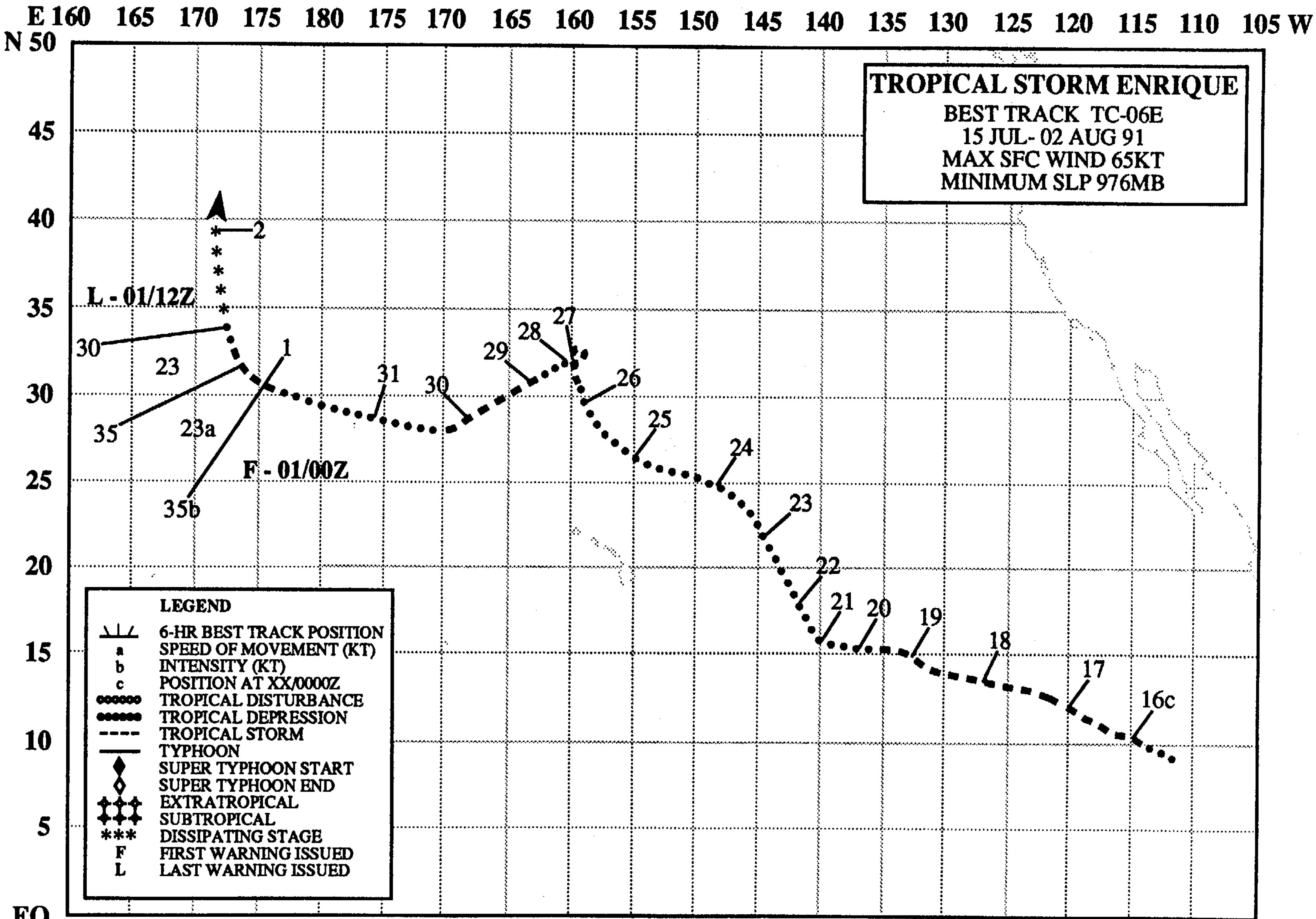
but the lack of continuity between successive warnings undermined confidence in the forecasts at a time when military units on Okinawa made the decision to evacuate. After shifting to its northward track forecast at 250000Z, JTWC forecast errors were exceptionally low, when compared with CLIPER and long term errors (Table 3-09-1). JTWC also outperformed OTCM at 24 and 48 hours.

IV. IMPACT

Caitlin provided welcome relief to the drought-stricken island of Okinawa. Kadena AB recorded a total of 12.51 inches (320 mm) of rain during a four day period, which was its heaviest precipitation since 1987. As a consequence, the reservoir level increased from only 35 percent to over 80 percent of its capacity. On Okinawa, one death was attributed to Caitlin, crop losses were estimated at $7.4 million, and U.S. military bases reported damage of more than $1.2 million. The typhoon enhanced the southwest monsoon across the northern Philippine Islands, and caused unwanted rainfall there. Manila received 8.38 inches (210 mm) of rain on 26 July, triggering avalanches of volcanic mud and debris, lahars, in the valleys near Mount Pinatubo and widespread flooding which resulted in 16 deaths and the evacuation of more than 20,000 people. Later, there were press reports of 2 deaths and over $4 million damage in Korea.

Table 3-09-1. Average 24-, 48-, and 72-hour forecast errors of the official forecast (JTWC) compared to CLIPER and OTCM for the time period 250000Z to 300000Z July, and the long term average JTWC errors.

	JTWC	CLIP	OTCM	Average
24 HR (17 cases)	70	81	91	120
48 HR (13 cases)	94	138	112	240
72 HR (09 cases)	146	266	126	360



TROPICAL STORM ENRIQUE
BEST TRACK TC-06E
15 JUL- 02 AUG 91
MAX SFC WIND 65KT
MINIMUM SLP 976MB
E 160 165 170 175 180 175 170 165 160 155 150 145 140 135 130 125 120 115 110 105 W
N 50 45 40 35 30 25 20 15 10 5 EQ
L - 01/12Z
F - 01/00Z
30
23
35
23a
35b
1
2
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16c
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TROPICAL STORM ENRIQUE (06E)

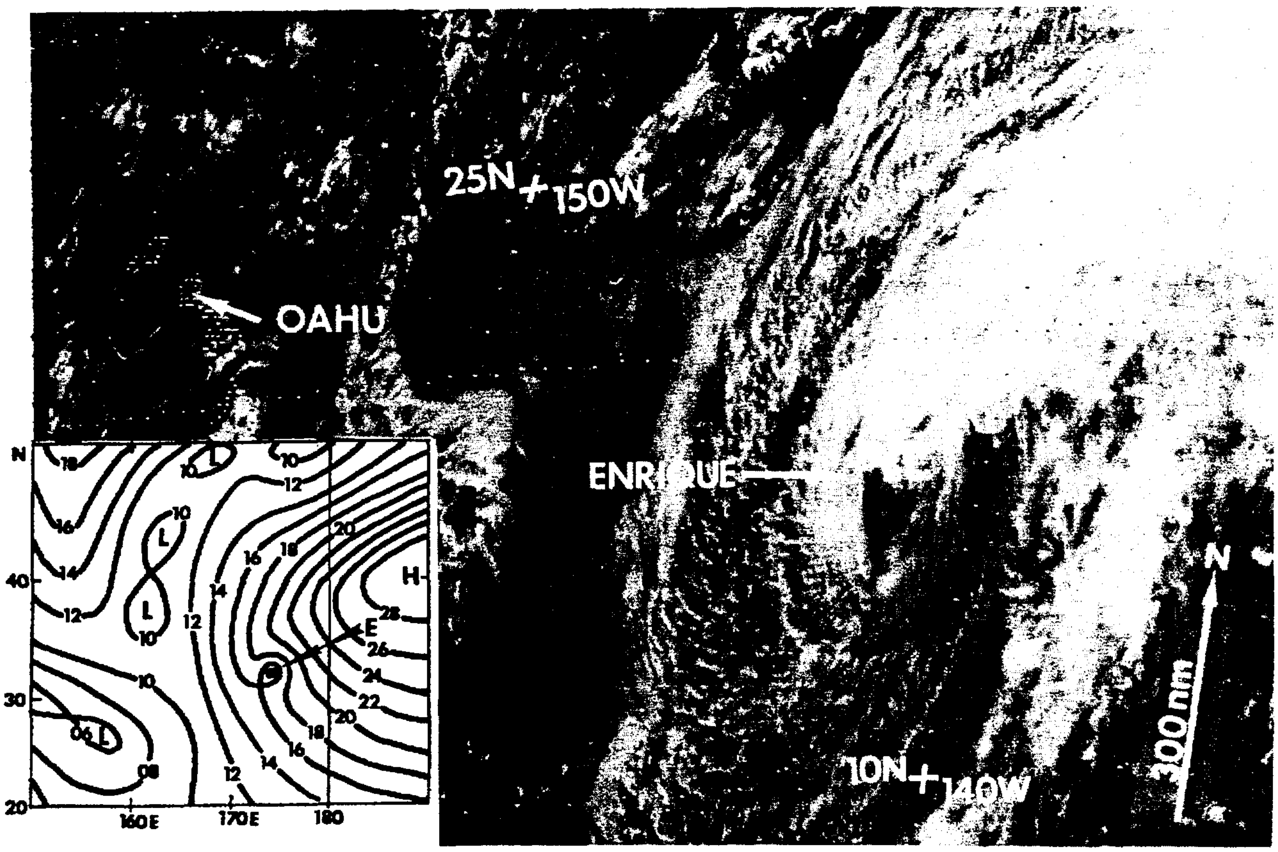
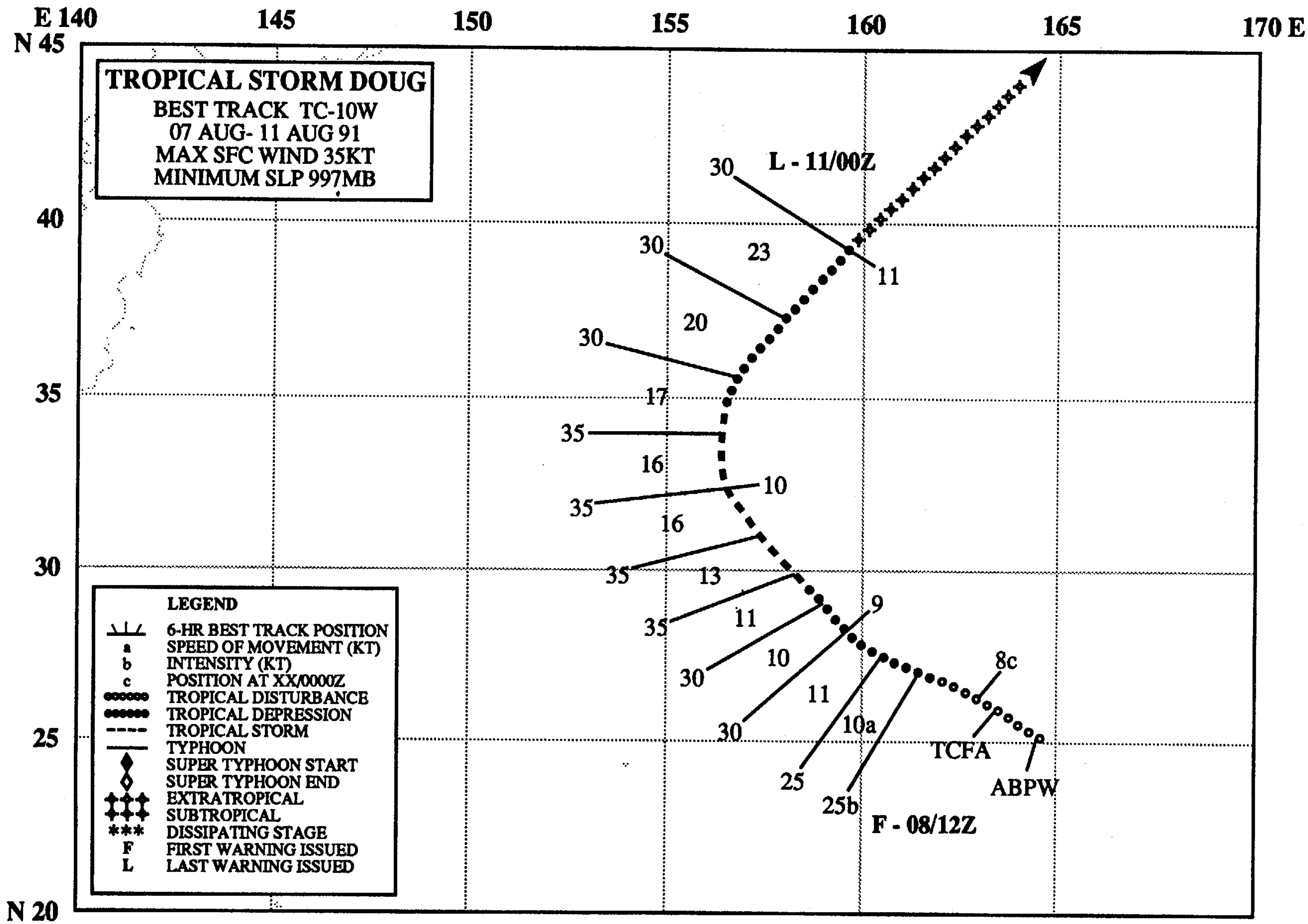


Figure 3-06E-1 Tropical Storm Enrique as a dissipating circulation east of the Hawaiian Islands (220000Z July GOES visual imagery).

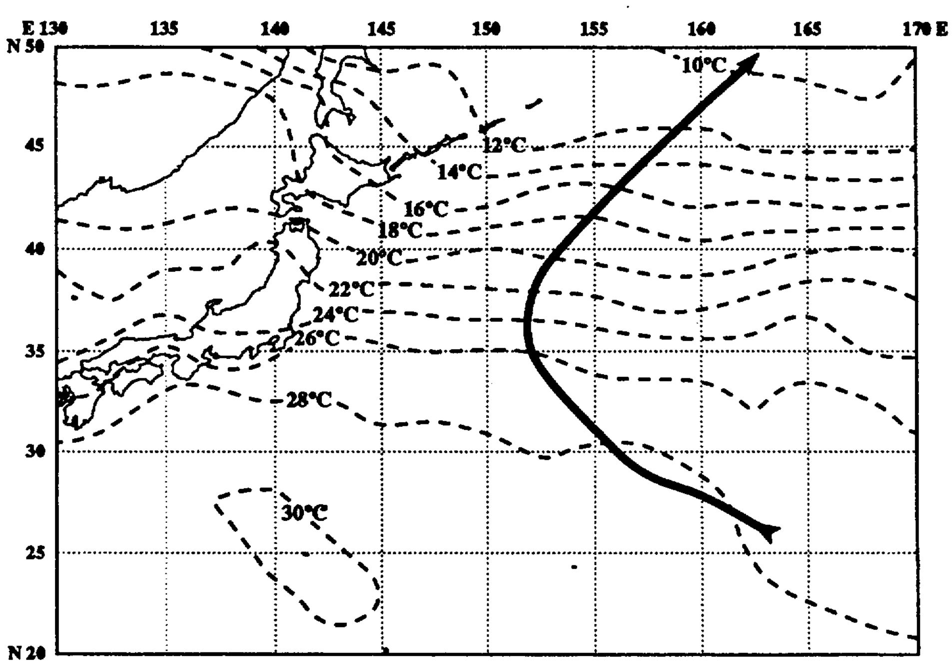
Enrique was a rare tropical cyclone that was warned on by three separate U.S. tropical cyclone warning centers. Enrique began in the Eastern Pacific, the National Hurricane Center's area of responsibility, trekked 4900 nm (9100 km) across the North Pacific Ocean through the Central Pacific Hurricane Center's area, then after weakening, regenerated and dissipated in JTWC's area of responsibility. Over the past 20 years, Typhoon Georgette (1986) was the only other Eastern Pacific tropical cyclone to cross the international date line. After the first warning was issued by the National Hurricane Center at 151800Z, Enrique tracked west-northwestward and intensified to minimal hurricane intensity at 170600Z before weakening as it approached 140°W. Enrique maintained a weak circulation during the next five days as it passed north of the Hawaiian Islands. Then, on 27 July, it executed a clockwise loop and headed southwestward while re-intensifying to 45 kt (23 m/sec). Increased vertical wind shear caused the circulation to weaken once again as it headed toward Midway Island. Visual satellite imagery of the small system at 291938Z revealed that it had a spiral low-cloud pattern indicative of a closed surface circulation. This prompted the JTWC to mention the small circulation on the 300600Z Significant Tropical Weather Advisory. Increased convection and a pressure fall of 7 mb observed at Midway Island (WMO 91066) as the system passed to the north led JTWC to issue a warning at 010000Z August. Enrique's tiny pressure signature was deeply embedded in the large maritime high to the northeast (as shown in the insert). As the tropical storm tracked to the north-northwest, it encountered strong upper-level wind shear and, once again, lost all of its deep convection. The last warning was issued at 011200Z.

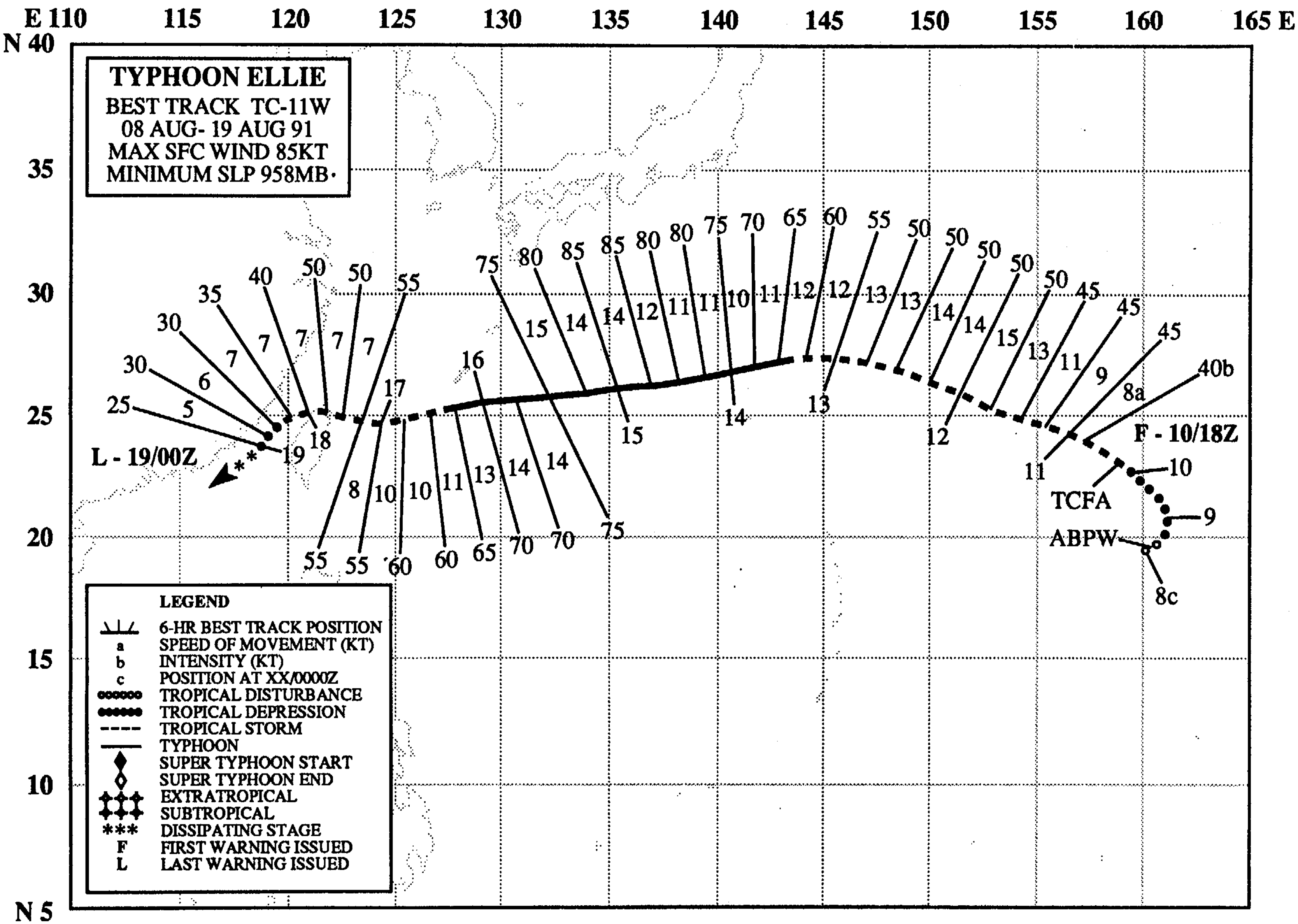

E 140
145
150
155
160
165
170 E
N 45
40
35
30
25
N 20
TROPICAL STORM DOUG
BEST TRACK TC-10W
07 AUG- 11 AUG 91
MAX SFC WIND 35KT
MINIMUM SLP 997MB
L - 11/00Z
F - 08/12Z
TCFA
ABPW
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TROPICAL STORM DOUG (10W)

Figure 3-10-1 Tropical Storm Doug heads northwestward into colder waters (see lower left) as Typhoon Ellie (11W) begins to intensify (090311Z August NOAA visual imagery).

Doug was the first of a series of six tropical cyclones to form in August as part of a large NSS monsoon gyre (Lander, 1992). The tropical disturbance that became Doug was initially discussed in the 070600Z Significant Tropical Weather Advisory. A Tropical Cyclone Formation Alert was issued at 071955Z when convection developed around a well-defined low-level circulation center. Increased deep central convection prompted the first Tropical Depression warning at 081200Z. Doug was upgraded to a tropical storm 24-hours later as it tracked northwestward to the subtropical ridge axis, and then recurved ahead of a mid-tropospheric trough. Doug failed to intensify beyond minimal tropical storm intensity because it moved rapidly northward into an area of colder sea surface temperatures and increased vertical shear before transitioning into an extratropical cyclone.




TYPHOON ELLIE
BEST TRACK TC-11W
08 AUG- 19 AUG 91
MAX SFC WIND 85KT
MINIMUM SLP 958MB
E 110
115
120
125
130
135
140
145
150
155
160
165 E
N 40
35
30
25
20
15
10
N 5
L - 19/00Z
F - 10/18Z
TCFA
ABPW
40b
8a
8c
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TYPHOON ELLIE (11W)

I. HIGHLIGHTS

The second tropical cyclone of August, Typhoon Ellie, formed as part of a larger NSS monsoon gyre (Lander, 1992) a day after Doug (10W) formed. Ellie, also the second midget typhoon of 1991, maintained a generally westward track 2400 nm (4440 km) across the western North Pacific from just west of Wake Island to Taiwan.

II. TRACK AND INTENSITY

After its initial counter-clockwise orbit of the center of the larger NSS monsoon gyre on 8 and 9 August, Ellie tracked westward, embedded in the mid-level flow south of the axis of a narrow subtropical ridge. Instead of recurving immediately behind Doug (10W), Ellie took a more westerly track as increased subsidence behind the passing mid-tropospheric trough associated with Doug (10W) caused ridging between the two tropical cyclones. Later, after crossing northern Taiwan and losing its central convection, the midget's residual vortex was carried southwestward with the low-level flow.

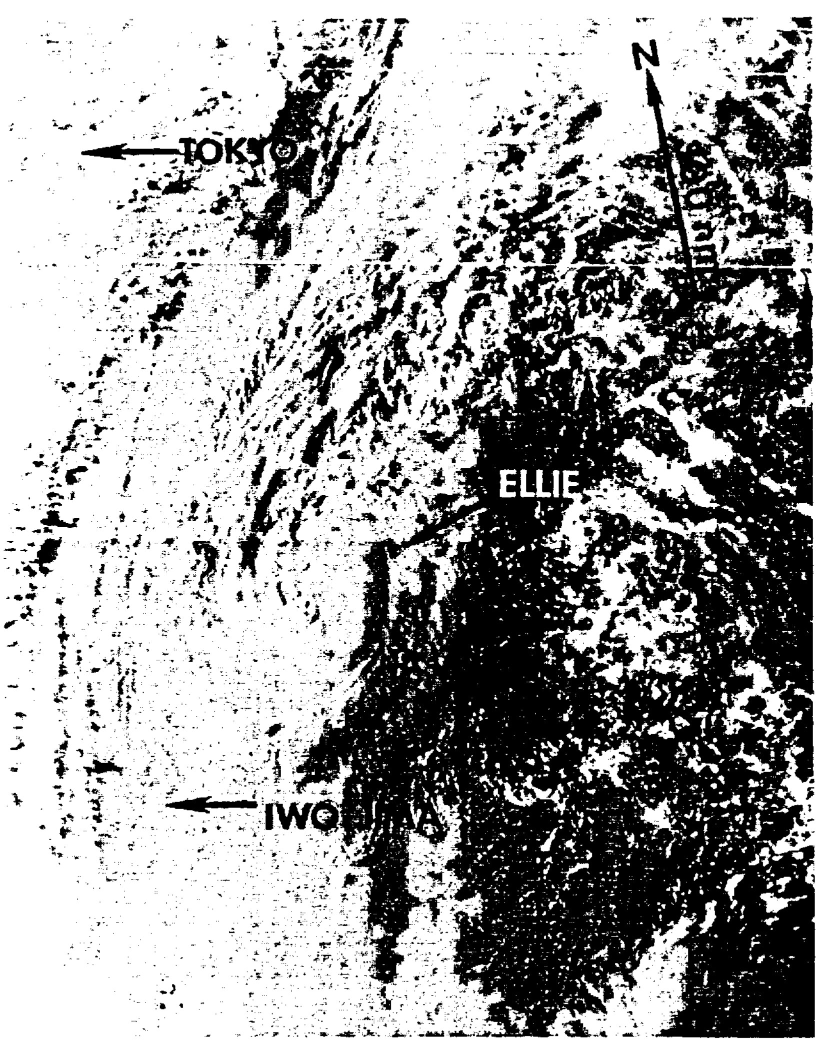


Figure 3-11-1. Ellie is upgraded to a typhoon as it develops a visible eye (130838Z August DMSP visual imagery).

Ellie developed as a weak disturbance between Wake Island and Minami-Tori Shima, and was first mentioned on the 080600Z Significant Tropical Weather Advisory. Visual satellite imagery at 100300Z showed that Ellie's central dense overcast (CDO) was very compact, and was associated with a low-level circulation. Synoptic data at the same time included a 25 kt (13 m/sec) wind report and a 1002 mb surface pressure nearby. Based on these data, JTWC issued a Tropical Cyclone Formation Alert at 100500Z. The first warning followed at 101800Z, and the system was upgraded to tropical storm intensity at 110000Z. The post analysis showed that this midget system actually had a central dense overcast and estimated winds of 35 kt (18 m/sec) at 100600Z. Ellie reached typhoon intensity at 131200Z (Figure 3-11-1) and later peaked at 85 kt (44 m/sec) at 141800Z (Figure 3-11-2). As Ellie began to weaken, the concentration and organization of the tropical cyclone's small CDO began to fluctuate. Increasing vertical shear and interaction with the mountainous island of Taiwan led to Ellie's demise and subsequent dissipation over water in the Taiwan Strait on 19 August.

III. FORECAST PERFORMANCE

The forecast aids, CLIM, CLIPER, AND HPAC, consistently called for recurvature (Figure 3-11-3). Initially, the dynamic and statistical-dynamical aids also favored a northwestward track through the subtropical ridge. As a result JTWC's forecasts initially reflected a recurvature scenario. Nevertheless Ellie moved south of the forecast break in the ridge and tracked to the west. Once the typhoon passed this weak bifurcation point, the dynamic models adopted an under-the-ridge scenario. Still, they sensed a weak ridge and, unable to account for the small size of the typhoon, continued to indicate that Ellie's track would gain latitude. In keeping with this dynamic guidance, JTWC's forecasts also provided predictions to the right of the verifying final best track. After the tropical cyclone moved southwest of Okinawa, and approximately 72 hours prior to dissipation, the dynamic aids began to sense the ridging over Asia and their track guidance moved closer to the actual track (Figure 3-11-4).

IV. IMPACT

Although Ellie persisted for over a week, threatened Okinawa, the southern Ryukyu Islands, northern Taiwan and maritime interests along the way, no reports of significant damage or fatalities were received.

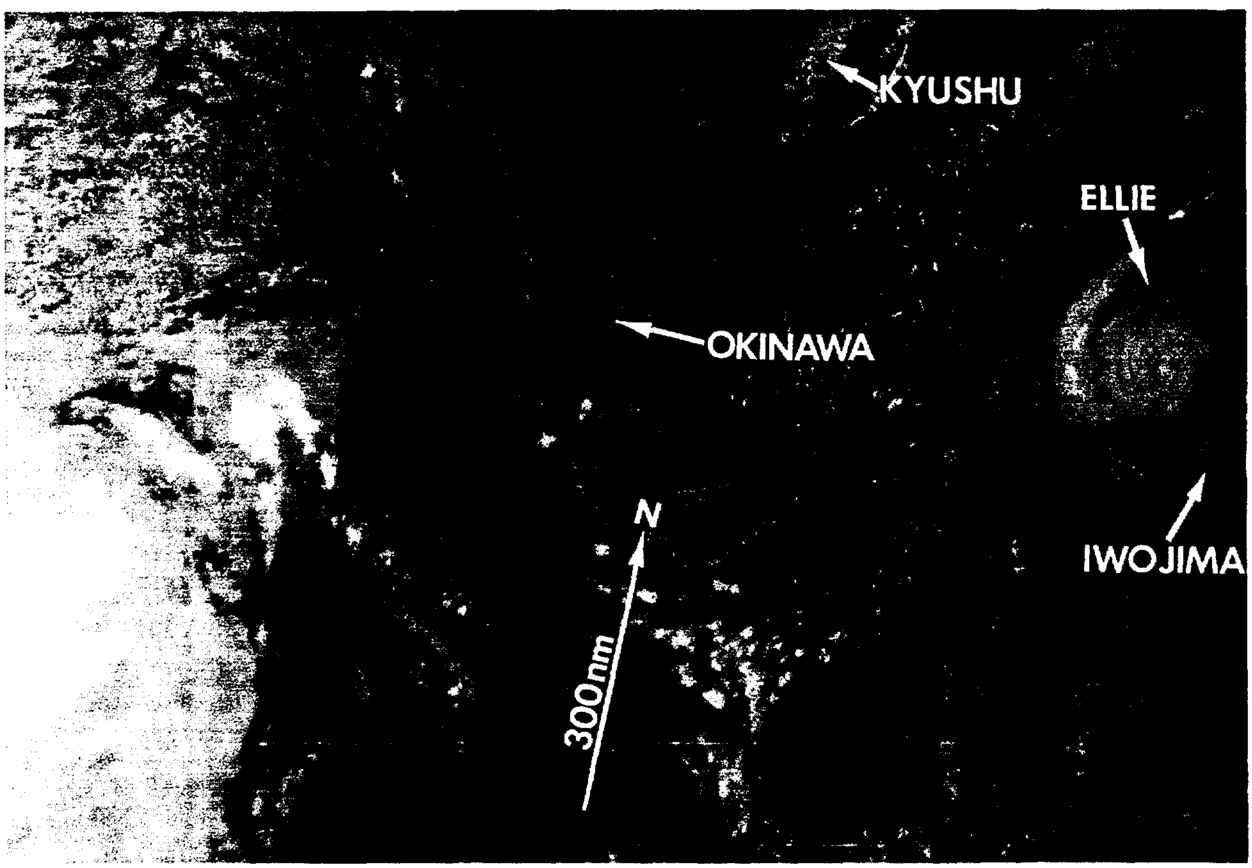
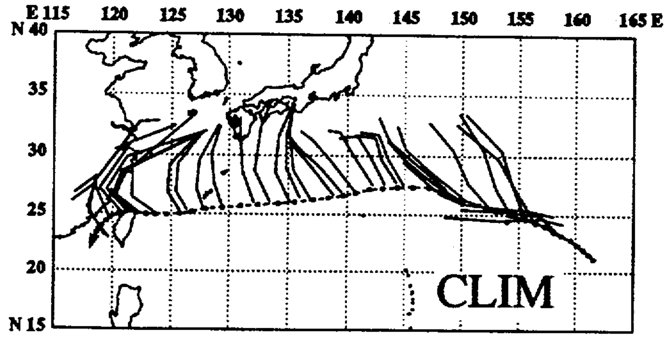


Figure 3-11-2. A partially cloud filled eye is visible as Ellie nears its maximum intensity in the northern Philippine Sea (140537Z August NOAA visual imagery).



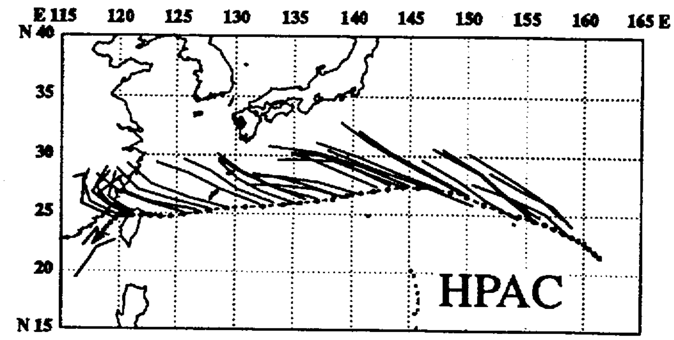
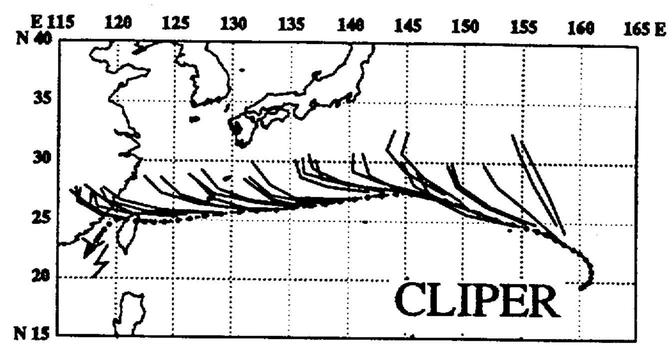
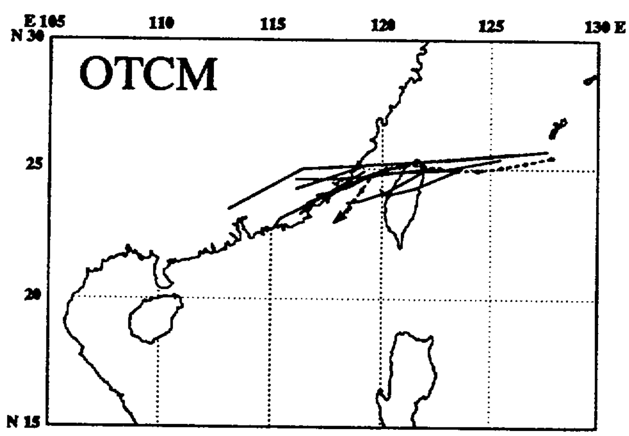
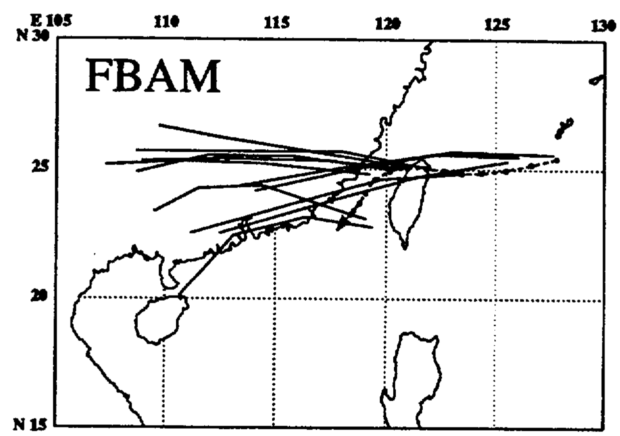


Figure 3-11-3. Climatological and statistical track guidance for Ellie (clockwise from top left): CLIMatology (CLIM), Half Persistence And Climatology (HPAC), CLImatology and PERsistence (CLIPER). These aids were consistently to the right of the verifying best track.







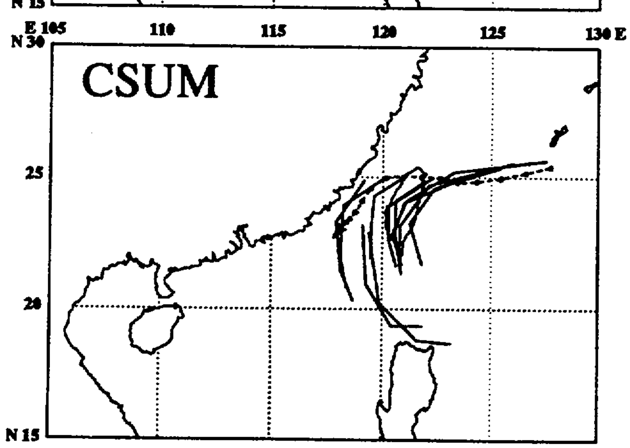
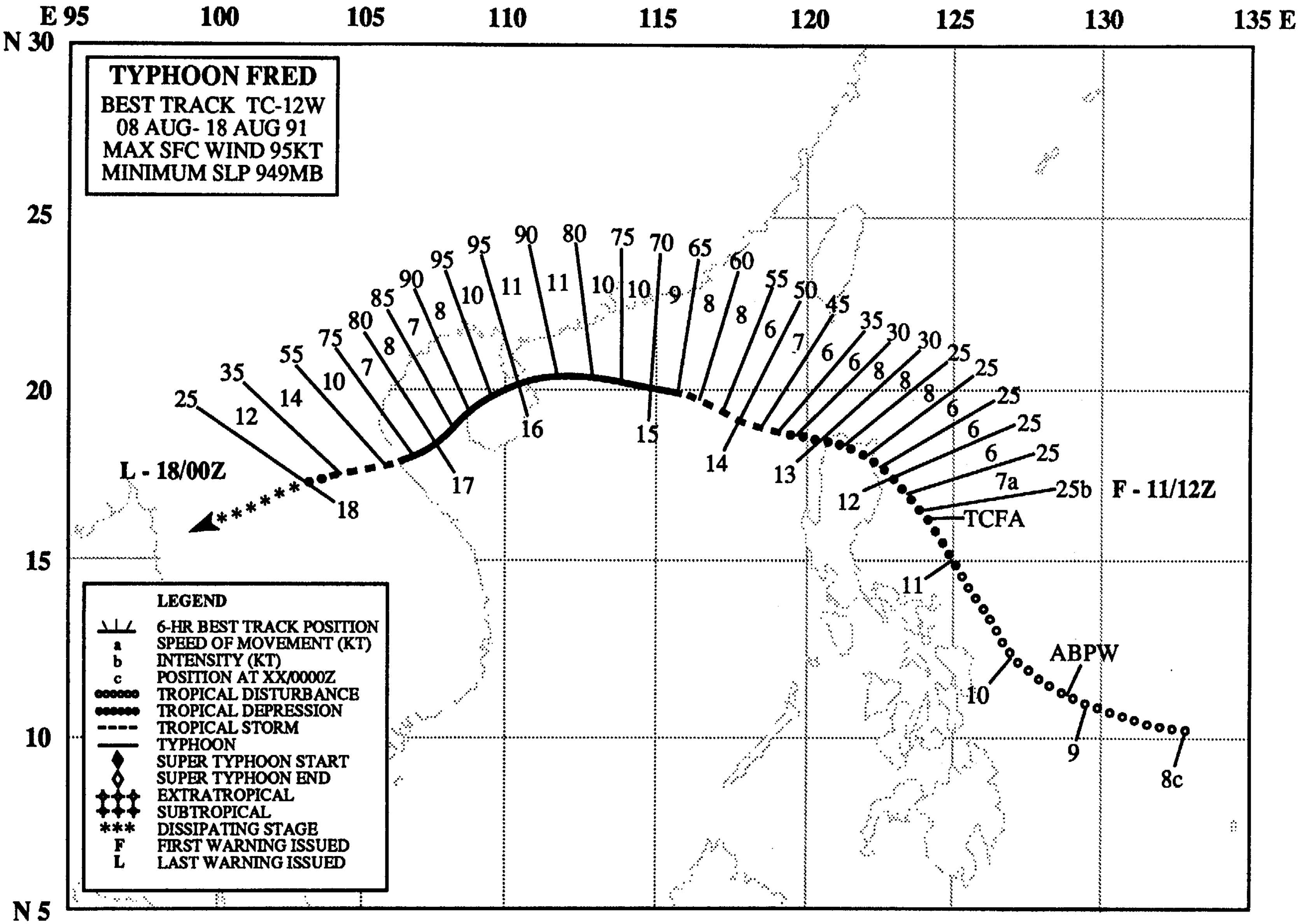


Figure 3-11-4. Objective guidance from the One-way Tropical Cyclone Model (OTCM), FNOC Beta and Advection Model (FBAM), and the Colorado State University Model (CSUM) correctly indicates westward to southwestward tracks after 160600Z as Ellie passed to the southwest of Okinawa.


TYPHOON FRED
BEST TRACK TC-12W
08 AUG- 18 AUG 91
MAX SFC WIND 95KT
MINIMUM SLP 949MB
E 95
100
105
110
115
120
125
130
135 E
N 30
25
20
15
10
N 5
L - 18/00Z
F - 11/12Z
TCFA
ABPW
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TYPHOON FRED (12W)

I. HIGHLIGHTS

Typhoon Fred was a part of two, three-storm outbreaks that occurred in mid-August. The first involved Typhoon Ellie (11W) and Tropical Depression 13W, and the second involved Ellie (11W) and Typhoon Gladys (14W). Fred skirted the northern coasts of Luzon and Hainan Island before dissipating over Southeast Asia. From the onset, JTWC correctly predicted that Fred would track generally to the west, and as a result, forecast track errors were very low, in fact, the lowest for any tropical cyclone of the year.

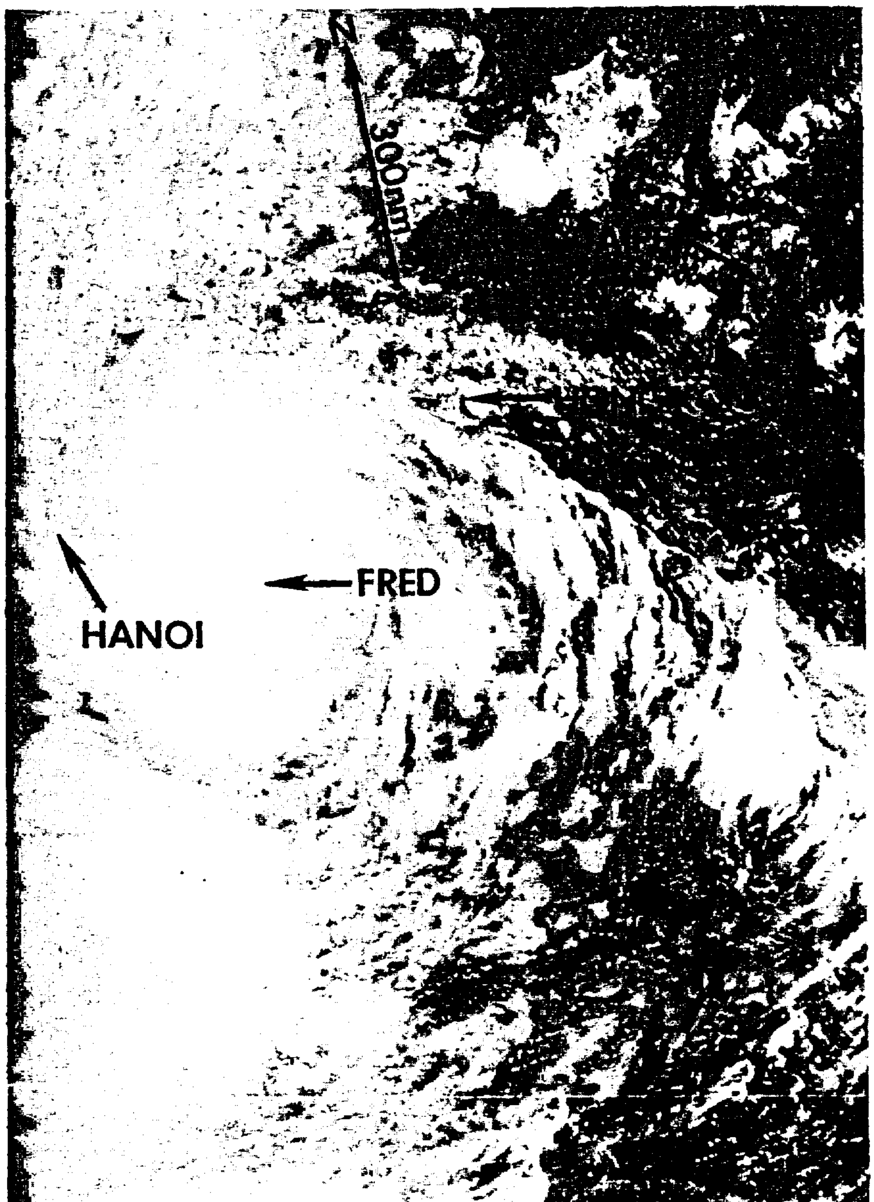


Figure 3-12-1. Typhoon Fred at minimal typhoon intensity, 120 nm (220 km) south of Hong Kong (150030Z August DMSP visual imagery).

II. TRACK AND INTENSITY

Fred originated as a broad, poorly organized circulation in the monsoon trough east of the central Philippine Islands on 8 August, and was first mentioned on the Significant Tropical Weather Advisory at 090600Z. A Tropical Cyclone Formation Alert was issued at 110900Z when animated satellite imagery revealed cyclonic motion of deep convective elements around a common center. The first warning on Tropical Depression 12W closely followed the alert, and was issued at 111200Z, when the "spin up" observed earlier from the satellite was supported by synoptic reports. After crossing northern Luzon, Fred headed west-northwestward, steered by a subtropical ridge which extended from the northern Philippine Sea southwestward into southern China. Intensifying as it moved west-northwestward, the tropical cyclone became a tropical storm at 131200Z and reached typhoon intensity at 141800Z (Figure 3-12-1), with the presentation of a visible eye in satellite imagery. On 15 August, the narrow ridge over southern China persisted and Typhoon Fred passed to the south of Hong Kong, heading for Hainan Dao. After passing along the northwest coast of Hainan Dao on 16 August with estimated maximum sustained winds of 95 kt (49 m/sec), the typhoon weakened and took an unanticipated southwestward track across the Gulf of Tonkin. Fred continued to track west-southwestward, and the final warning was issued at 180000Z as the low was dissipating over the mountainous terrain of Southeast Asia.

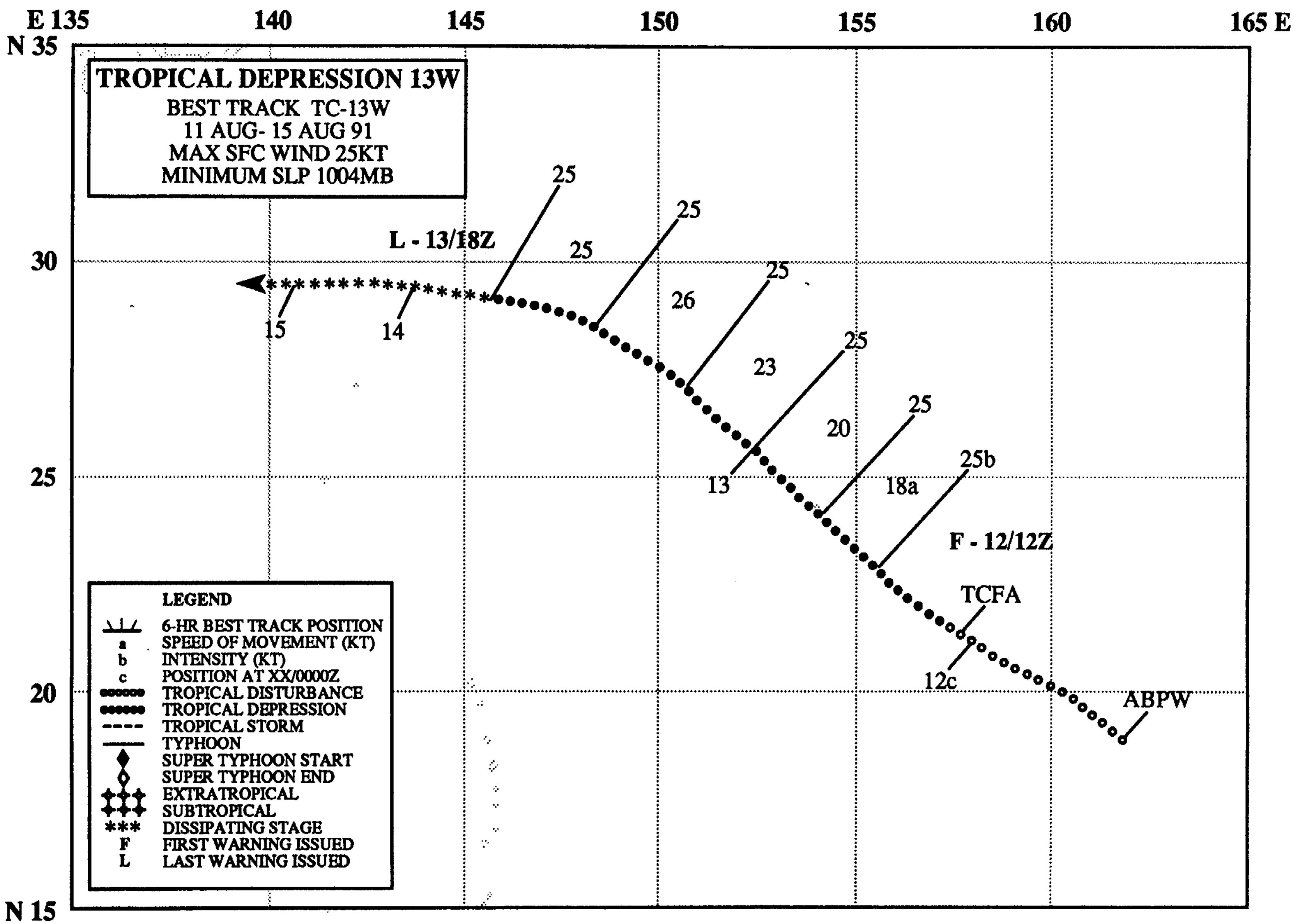
II. FORECAST PERFORMANCE

JTWC forecast performance on Typhoon Fred was noteworthy. Overall, mean forecast track errors were 65, 109, and 131 nm (120, 200 and 240 km) at 24, 48 and 72 hours, respectively. In comparison, the Persistence-Climatology model, CLIPER, had errors of 93, 195 and 339 nm (170, 360 and 630 km) for the same period. The early intensity forecasts correctly indicated that Fred would attain typhoon intensity in the South China Sea.

IV. IMPACT

Heavy rains fell on Luzon as Fred crossed the northern part of the island and triggered lahars or mudslides of volcanic ash and debris in the river valleys near Mount Pinatubo. Over 100 homes were destroyed and thousands of people were forced to evacuate areas near the volcano. A 20,000 ton oil exploration barge capsized and sánk 65 nm (120 km) east of Hong Kong on 15 August. Of the 195 crew members on board the 420 foot long **Derrick Barge 29,** 22 perished, including 4 divers who were trapped in a saturation diving chamber beneath the barge. At-sea rescues of the 173 survivors were accomplished by helicopter and tugboat. In the Chinese island province of Hainan, at least 16 died during Fred's passage.

Intentionally left blank.



E 135
140
145
150
155
160
165 E
N 35
30
25
20
N 15
TROPICAL DEPRESSION 13W
BEST TRACK TC-13W
11 AUG- 15 AUG 91
MAX SFC WIND 25KT
MINIMUM SLP 1004MB
L - 13/18Z
F - 12/12Z
TCFA
ABPW
25
25
25
25
26
25
23
25
20
25
25b
13
18a
12c
14
15
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TROPICAL DEPRESSION 13W

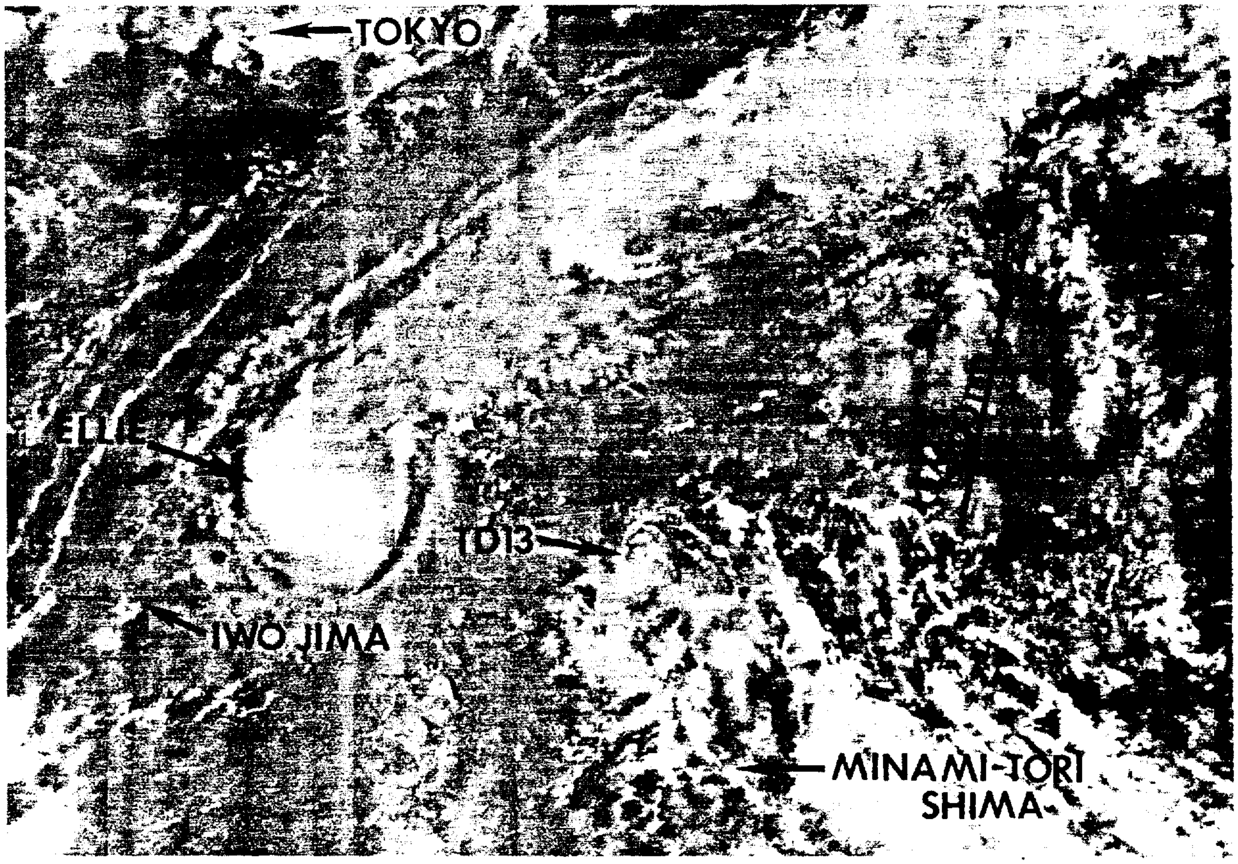
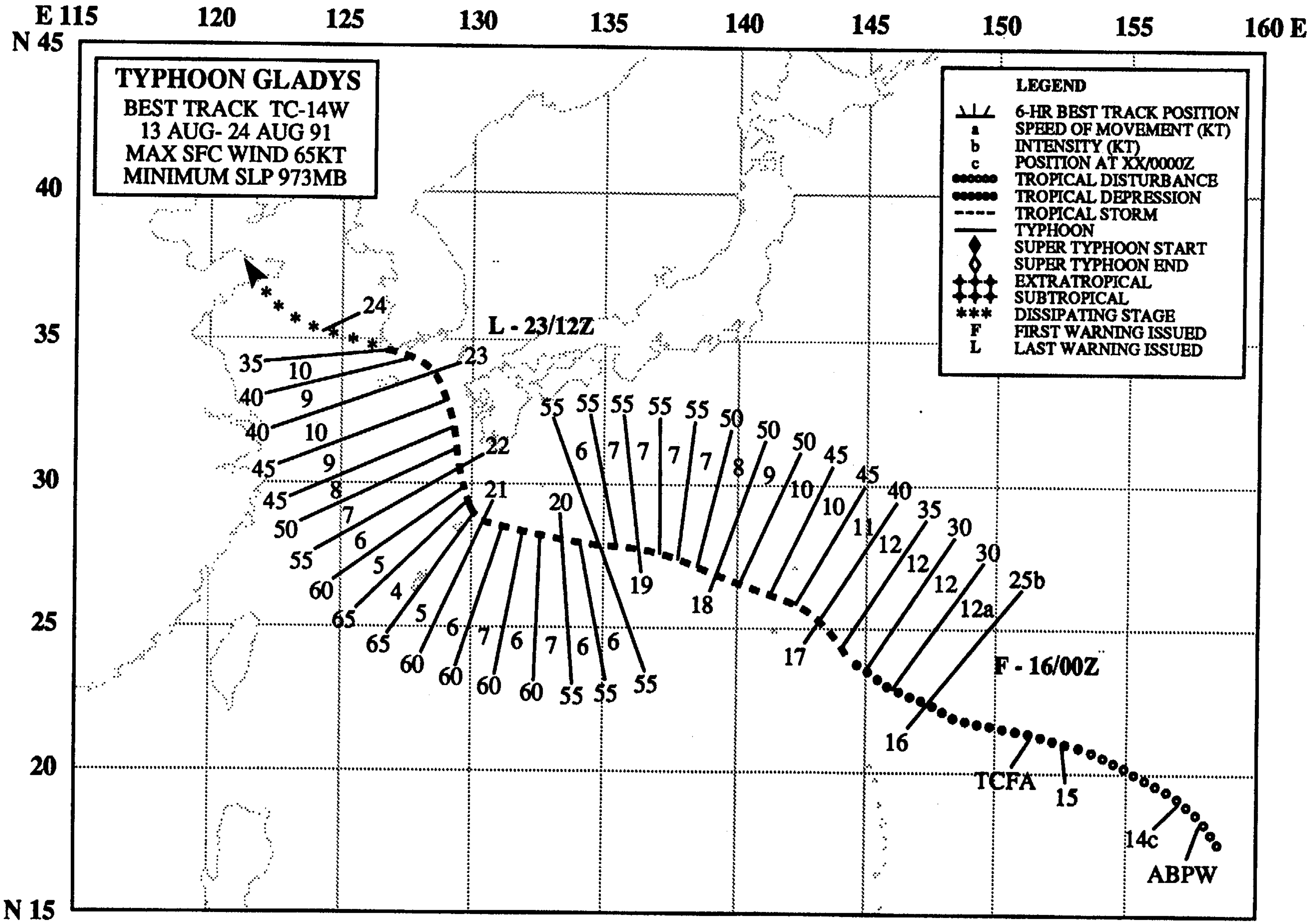


Figure 3-13-1 Tropical Depression 13W dissipates east of Typhoon Ellie (11W)(130406Z August NOAA visual imagery).

Tropical Depression 13W formed as a low pressure area in the same NSS monsoon gyre (Lander, 1992) as Typhoon Ellie (11W), and then tracked northwestward in Ellie's wake. Tropical Depression 13W was marked by large diurnal fluctuations in convection which slowed the development of strong surface winds. The disturbance was first mentioned on the Significant Tropical Weather Advisory at 110600Z. Following its next diurnal flare-up in convection, JTWC issued a Tropical Cyclone Formation Alert at 120130Z. Based on synoptic reports of 25 kt (13 m/sec) winds within 100 nm (185 km) of the circulation center and a Dvorak current intensity estimate of 25 kt (13 m/sec), the first warning was issued at 121200Z. Shortly afterward, convection decreased and visual satellite imagery of the remaining low-level circulation revealed that the cyclone center was poorly organized. When convection failed to redevelop around the center, JTWC issued its final warning on Depression 13W at 131800Z.


TYPHOON GLADYS
BEST TRACK TC-14W
13 AUG- 24 AUG 91
MAX SFC WIND 65KT
MINIMUM SLP 973MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
L - 23/12Z
F - 16/00Z
TCFA
ABPW
E 115
120
125
130
135
140
145
150
155
160 E
N 45
40
35
30
25
20
N 15

TYPHOON GLADYS (14W)

I. HIGHLIGHTS

Typhoon Gladys was the largest and the fourth of six tropical cyclones generated by a NSS monsoon gyre active during the month of August. While Gladys' wind field continued to expand as it tracked southwest of Japan, there was only a small change in minimum sea-level pressure, providing a good example of a cyclone that "strengthened" significantly but did not "intensify" significantly. Despite consistently outstanding track forecasts, JTWC over-forecast the cyclone's potential for intensification.

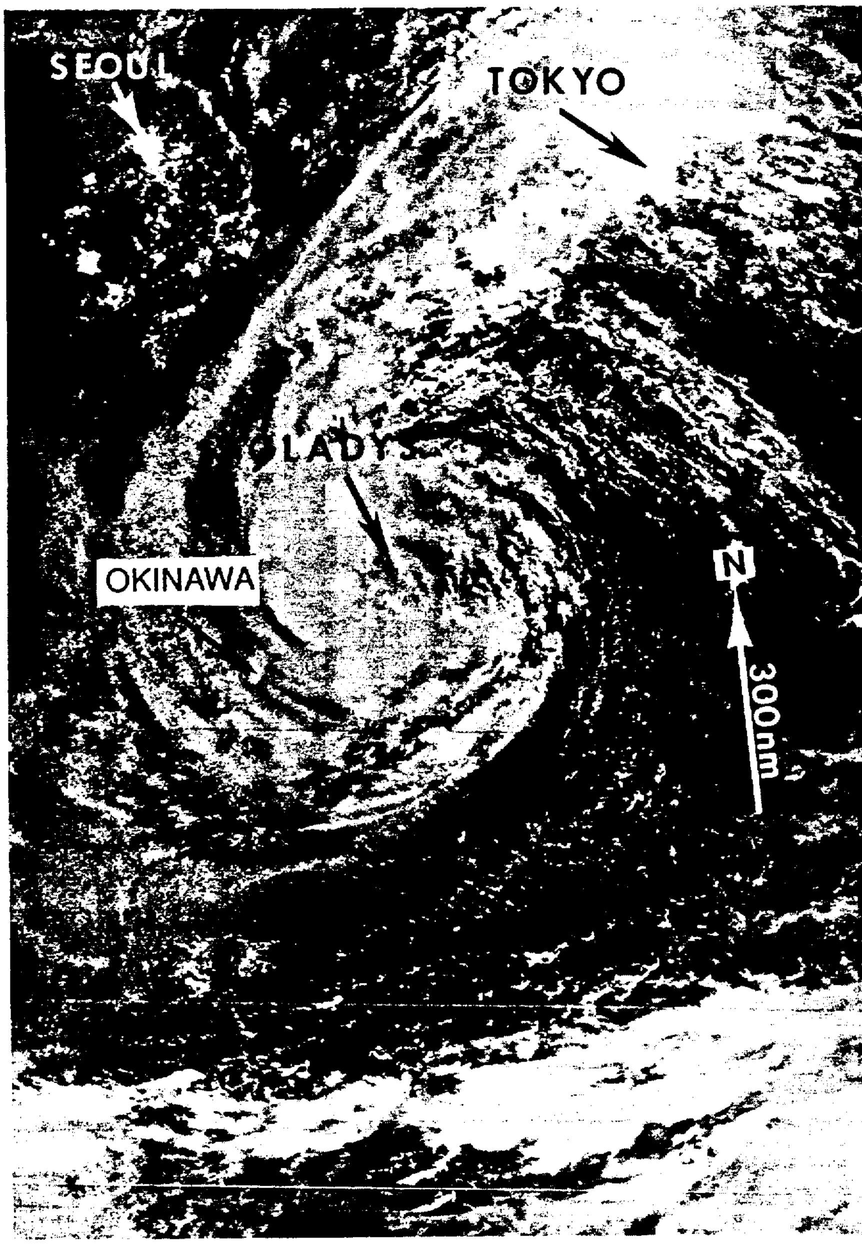


Figure 3-14-1. Tropical Storm Gladys approaches the northern Ryukyu Islands. At this time, land stations 360 nm (665 km) northeast of the center reported winds in excess of 35 kt (18 m/sec) (201235Z August DMSP moonlight visual imagery).

II. TRACK AND INTENSITY

Developing from an active NSS monsoon gyre in mid-August, Gladys tracked west-northwestward for most of its lifetime, south of an east-west oriented subtropical ridge. Initially described on the 131800Z Significant Tropical Weather Advisory as a weak cyclonic circulation, it slowly gained convective organization over the next two days, and a Tropical Cyclone Formation Alert was issued at 150730Z. The first warning (160000Z) on Tropical Depression 14W was based on increased curvature in the spiral convective bands. Then after receipt of several synoptic wind reports of 30 kt (15 m/sec), the cloud system was upgraded to a tropical storm at 161800Z.

The most distinctive characteristic of Gladys was its large size (Figure 3-14-1). Ships and island stations reported an increasingly large area of gale-force winds surrounding the poorly organized circulation. Because of its large size, it was hypothesized that beta drift added a northward component of motion to the westward-oriented track.

The effect of beta drift may have been demonstrated in the fact that Gladys tracked to the right of the dynamic forecast aid, OTCM (Figure 3-14-2). The large displacement of maximum winds far from the cyclone's broad center and the absence of deep convection may have prevented a normal rate of intensification (Weatherford, 1985). For most of its life, Gladys intensified at a slow rate of only 5 kt (3 m/sec) per day, reaching minimal typhoon intensity near Amami-shima, 90 nm (165 km) northeast of Okinawa. The weather station on Amami-shima (WMO 47909) recorded 64 kt (33 m/sec) gradient-level winds and a minimum sea-level pressure of 973 mb as the cyclone center passed within 35 nm (65 km) of the island. After clearing the northern Ryukyu Islands, a fast-moving mid-tropospheric trough induced Gladys to turn north-northwestward. As the trough passed, vertical shear increased on the poleward side of Gladys' cloud mass, and the central pressure of the system began to rise. Reestablishment of the mid-tropospheric subtropical ridge over the Sea of Japan on 22 August prevented recurvature, and Gladys tracked toward the southern coast of Korea. The final warning was issued at 231200Z when the combined effects of increasing shear and land interaction indicated that the circulation was weakening rapidly.

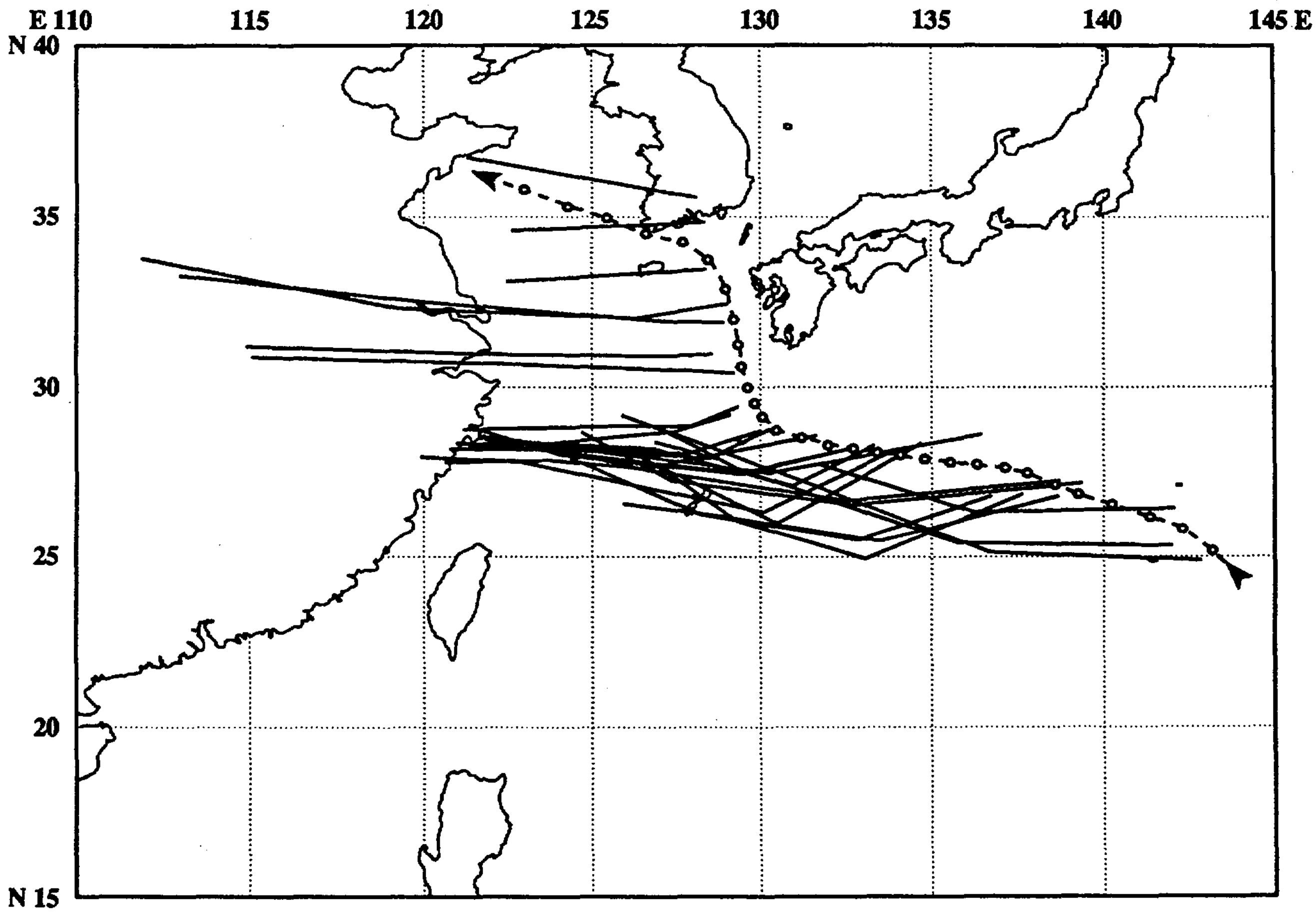


Figure 3-14-2. 160000Z to 231200Z August time series of One-Way (Interactive) Tropical Cyclone Model (OTCM) forecasts versus the official best track. OTCM's poor performance during the entire lifetime of Typhoon Gladys can be partially explained by the beta effect of large tropical cyclones.

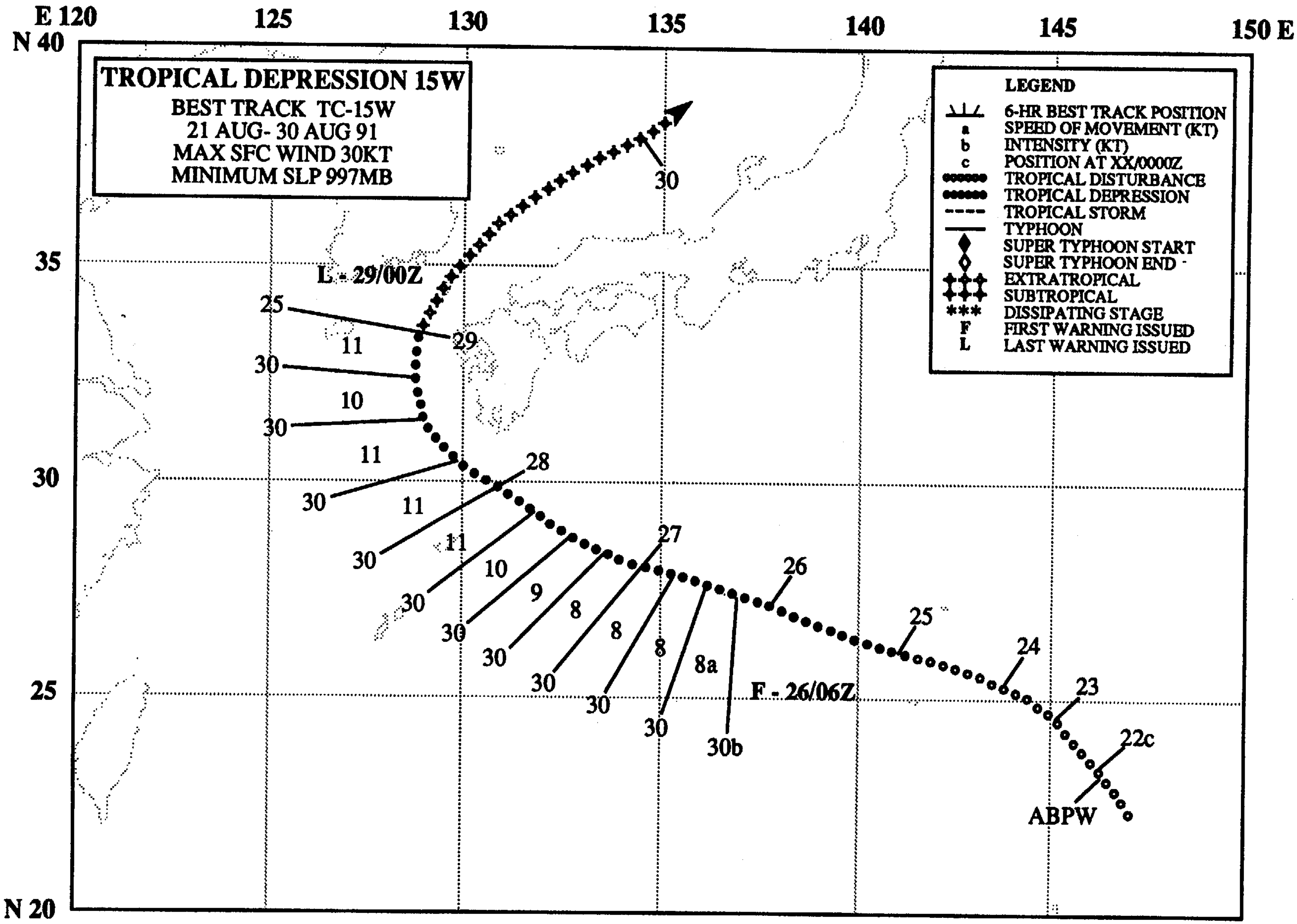
III. FORECAST PERFORMANCE

JTWC motion forecasts of Typhoon Gladys were quite accurate; in fact, only one warning had 72-hour forecast errors larger than 300 nm (555 km). Of note is the fact that JTWC correctly predicted that the cyclone would not recurve, even as it turned north-northwestward near Kyushu. In contrast, other tropical cyclone warning centers in the region predicted that Gladys would recurve through the Korea Strait, between Tsushima and western Kyushu. The divergent forecasts increased the potential for conflicting information to reach operational decision makers in Korea and Japan. During this period, JTWC provided extensive, detailed prognostic reasoning messages which, in conjunction with the warning bulletins and telephone discussions, evaluated the potential for the possible forecast scenarios and helped allay operational concerns.

Intensity forecast performance was poor because Gladys was expected to reach a maximum intensity much greater than 65 kt (33 m/sec). At 161200Z, when the system was only a tropical depression, JTWC predicted it would rapidly intensify to a peak intensity of 120 kt (62 m/sec) in 72 hours, and for the next seven warnings peak winds in excess of 100 kt (51 m/sec) were forecast. As a result, wind errors for the duration of the forecast period were among the highest of the season. In post-analysis, most of the large wind errors could have been avoided if a simple equation relating latitude and peak intensity had been used (Mundell, 1990).

IV. IMPACT

Typhoon Gladys' huge circulation caused record amounts of rainfall in Korea and Japan. South Korea's Disaster Relief Center reported at least 90 people were killed or missing, 62 injured, and 40,000 left homeless. The center estimated property loss at nearly US $45 million. Pusan, Korea's second largest city, received 24 inches (610 mm) of rain in 20 hours and sections along the southeast coast were reported to have received 26 inches (660 mm) during the same period. In addition, Gladys dumped as much as 28 inches (710 mm) of rain on central Japan, triggering landslides which killed 10 people west of Tokyo and flooded at least 1,000 homes.


TROPICAL DEPRESSION 15W
BEST TRACK TC-15W
21 AUG- 30 AUG 91
MAX SFC WIND 30KT
MINIMUM SLP 997MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 120
125
130
135
140
145
150 E
N 40
35
30
25
N 20
L - 29/00Z
F - 26/06Z
ABPW
22c
30b
8a

TROPICAL DEPRESSION 15W

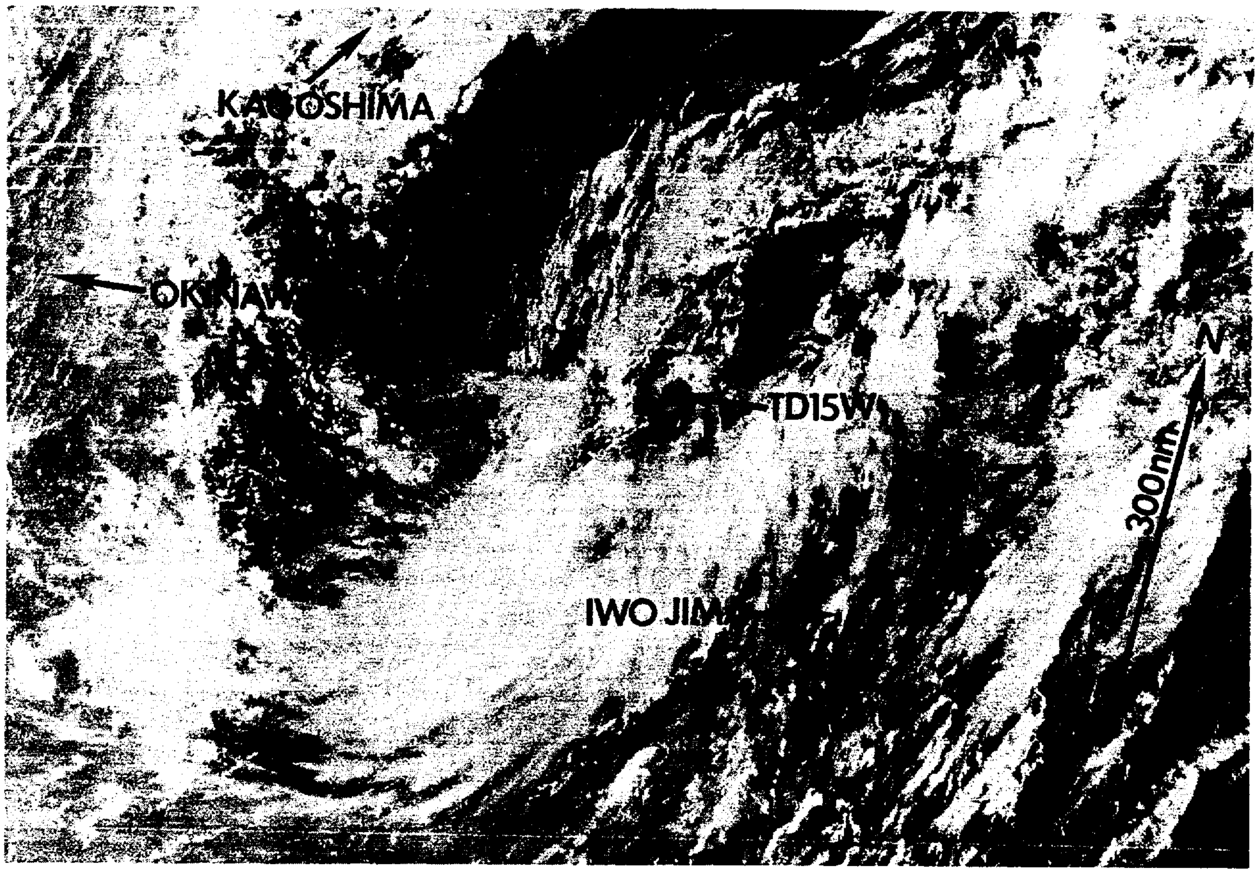
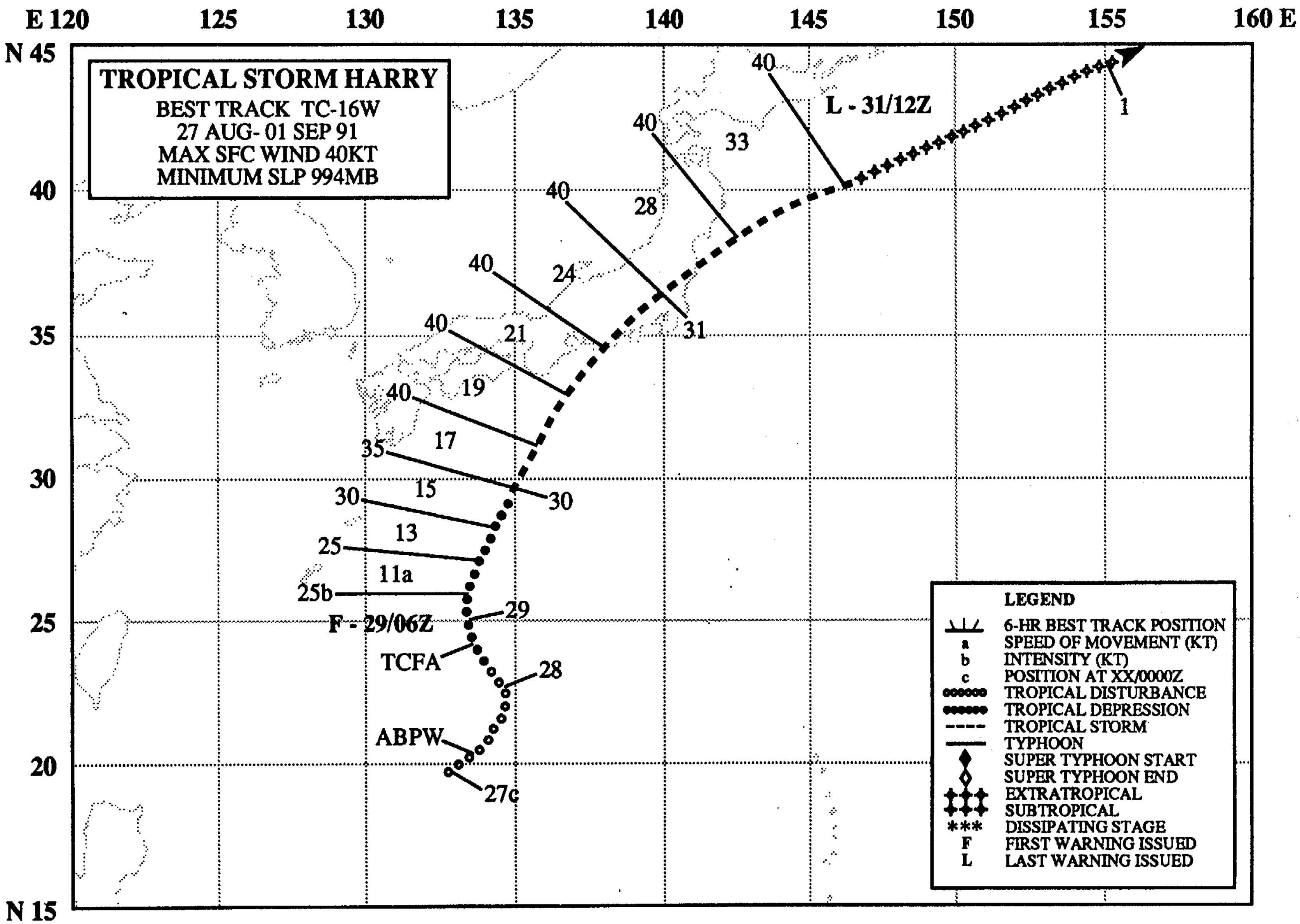


Figure 3-15-1 The well-defined center of Tropical Depression 15W, as seen 6 hours prior to the first warning on the system (252327Z August DMSP visual imagery).

When animated satellite imagery indicated cyclonic turning in an area of deep convection associated with a NSS monsoon gyre (Lander, 1992), a Significant Tropical Weather Advisory was reissued at 212200Z (August) to include the disturbance that was to become Tropical Depression 15W. For the next four days, a single, well-defined circulation center failed to develop. Then, following receipt of a ship report indicating 39 kt (20 m/sec) sustained winds and a surface pressure of 998 mb, the first warning on Tropical Depression 15W was issued at 260600Z. A Tropical Cyclone Formation Alert did not precede the first warning, and the minimal tropical storm intensity indicated by the earlier ship report was discounted due to the continued presence of a shear-type cloud pattern. The depression moved west-northwestward, south of Japan, recurved through a break in the subtropical ridge, and dissipated in the Sea of Japan. It is thought that Tropical Depression 15W did not intensify further because persistent vertical wind shear prevented the development of a persistent central dense overcast.



TROPICAL STORM HARRY
BEST TRACK TC-16W
27 AUG- 01 SEP 91
MAX SFC WIND 40KT
MINIMUM SLP 994MB
E 120
125
130
135
140
145
150
155
160 E
N 45
40
35
30
25
20
N 15
L - 31/12Z
F - 29/06Z
TCFA
ABPW
25b
11a
27c
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TROPICAL STORM HARRY (16W)

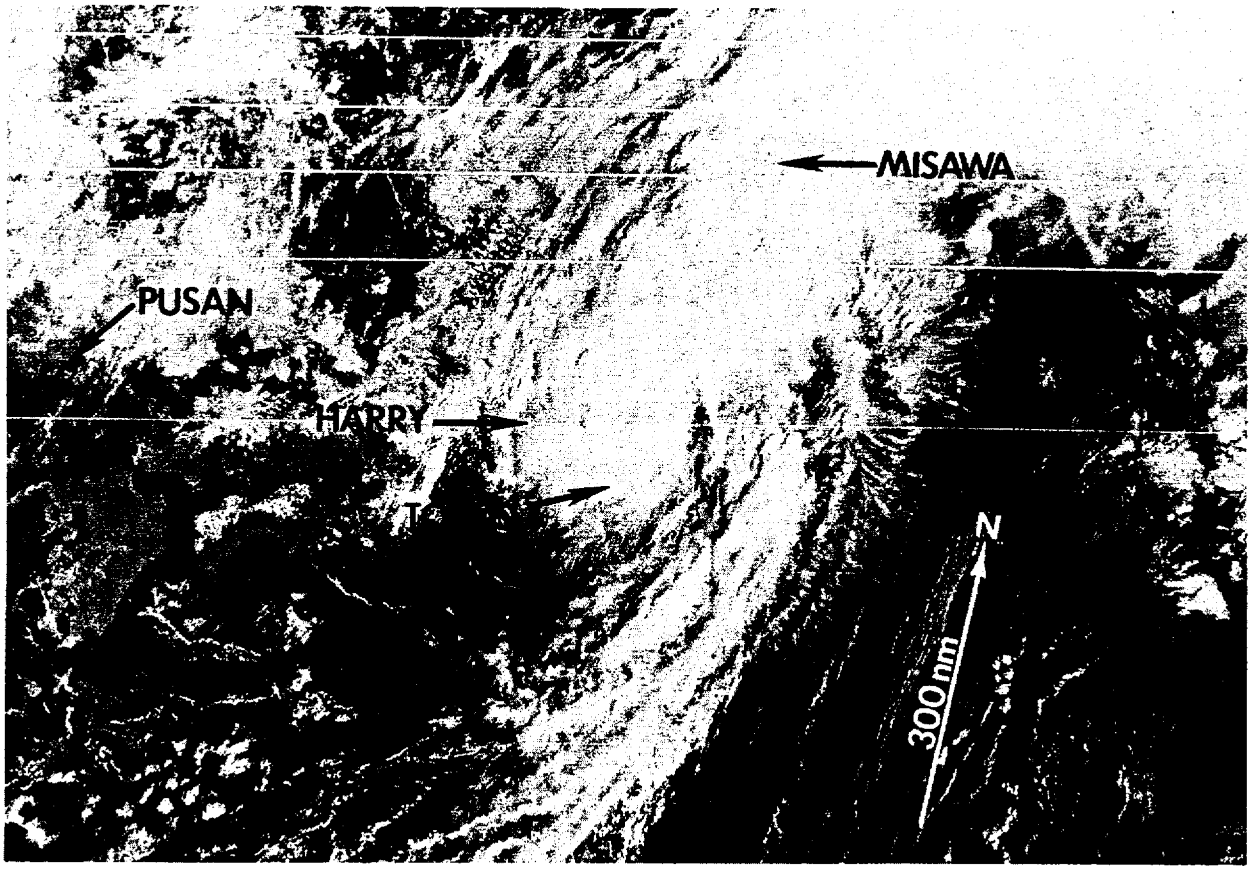
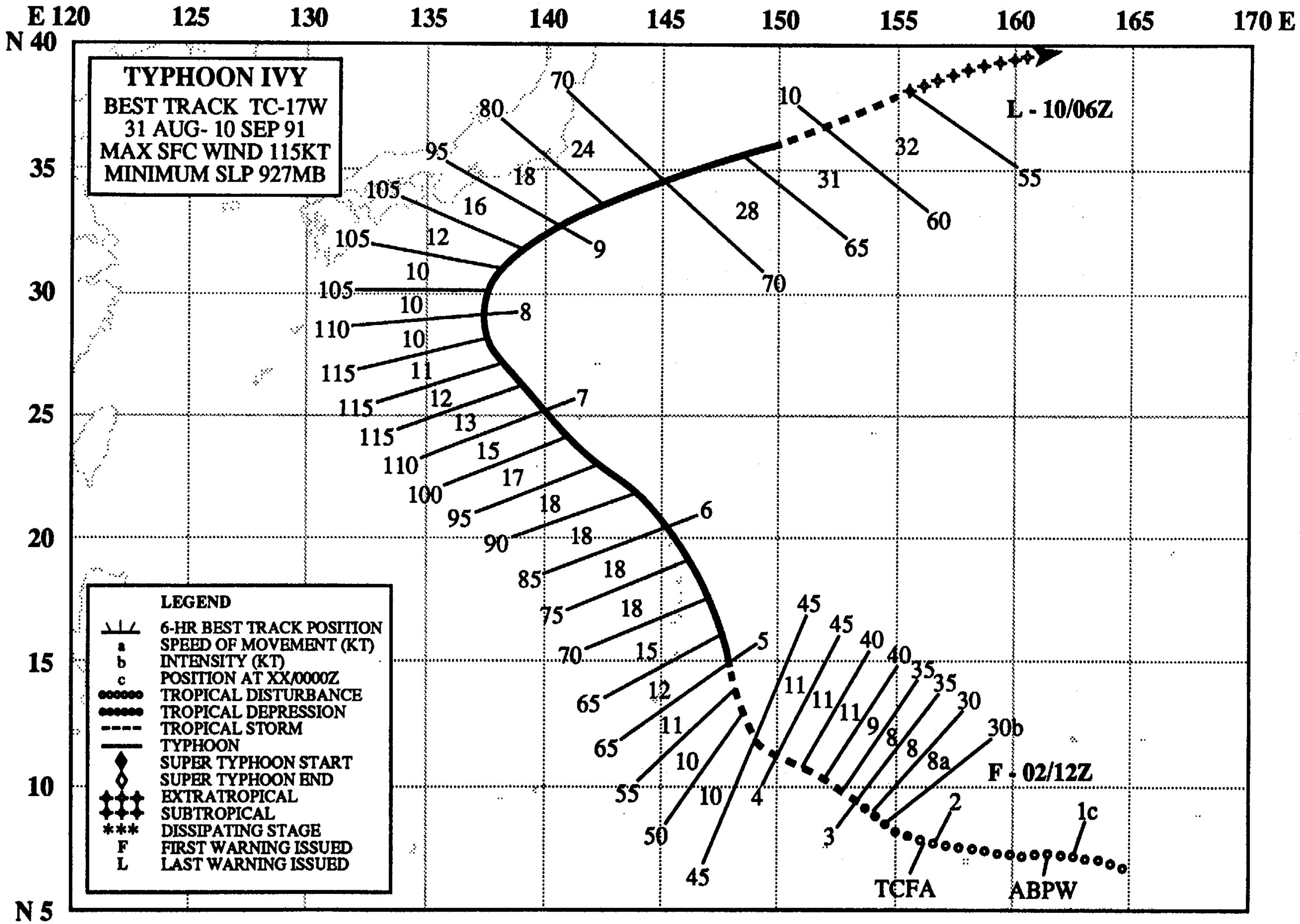


Figure 3-16-1 Tropical Storm Harry crosses the southern coast of Honshu (302320Z August DMSP visual imagery).

Harry was initially detected in the northern Philippine Sea as a poorly organized cyclonic circulation in a NSS monsoon gyre, and was mentioned on the 270600Z August Significant Tropical Weather Advisory. Harry became the last of six tropical cyclones, beginning with Doug (10W) three weeks earlier, to generate within this NSS monsoon gyre. At 281800Z, ship reports of 25 to 30 kt (13 to 15 m/sec) and increased convection on the south side of the circulation prompted the issuance of a Tropical Cyclone Formation Alert. JTWC issued the first warning on Harry at 290600Z. Harry moved northward through a break in the subtropical ridge, recurved and accelerated across the southeastern coast of Honshu near the coastal city of Hamamatsu, which is located 115 nm (215 km) southwest of Tokyo. Weak surface wind reports suggested that the tropical cyclone had no significant impact on the Tokyo metropolitan area. The final warning was issued at 311200Z, when Harry became an extratropical cyclone.


TYPHOON IVY
BEST TRACK TC-17W
31 AUG- 10 SEP 91
MAX SFC WIND 115KT
MINIMUM SLP 927MB
E 120
125
130
135
140
145
150
155
160
165
170 E
N 40
35
30
25
20
15
10
N 5
L - 10/06Z
F - 02/12Z
TCFA
ABPW
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TYPHOON IVY (17W)

I. HIGHLIGHTS

Ivy was the first tropical cyclone to form in the monsoon trough which established itself eastward through the Caroline Islands. Ivy was also the first significant threat of the typhoon season to the Mariana Islands. For 4 days, the tropical cyclone tracked west-northwestward, straight towards Guam, then on 4 September took a sudden, unanticipated turn to the north-northwest and headed for the Northern Marianas and Japan.

II. TRACK AND INTENSITY

Ivy developed in a broad monsoon trough near Kosrae in the eastern Caroline Islands. It was first mentioned on the 010600Z September Significant Tropical Weather Advisory when a consolidated area of convection started to flare up along the trough. As the convection became more organized, a Tropical Cyclone Formation Alert was issued at 020200Z, followed by a warning at 021200Z. Initially, Ivy was difficult to locate precisely as it developed a broad, glaciated central dense overcast. On 4 September, a southwesterly monsoon surge linked up with the cyclone, adding even more diffuse cloudiness (Figure 3-17-1). The surge then sharply pushed the tropical cyclone to the north-northwest, against the western periphery of the subtropical ridge. As Ivy moved northward, it began to rapidly

Figure 3-17-1. Satellite imagery depicts the southwest monsoon cloudiness approaching Ivy while the tropical storm tracks west-northwestward (041214Z September DMSP infrared imagery).

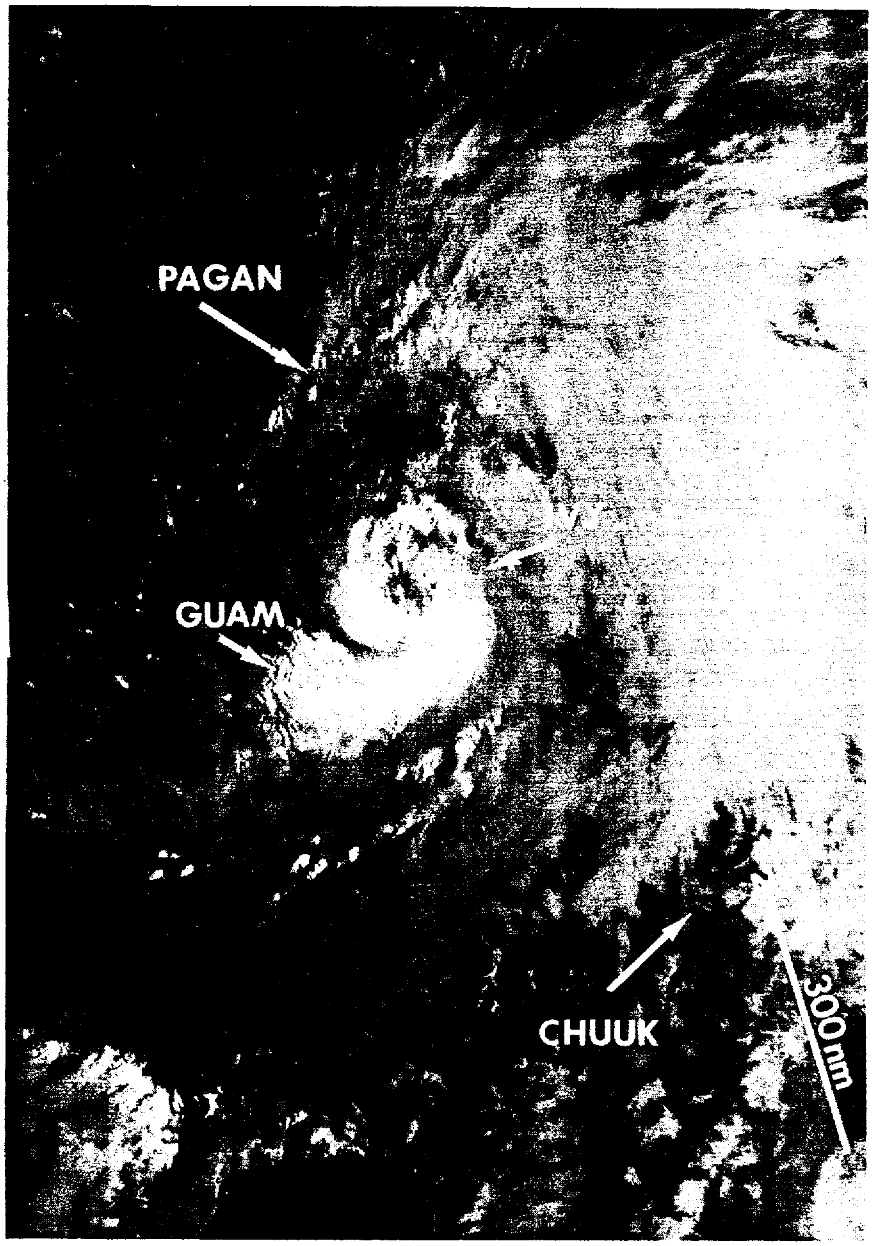


Figure 3-17-2. Satellite imagery 10 hours after Figure 3-17-1 shows Ivy as it reaches typhoon intensity (042242Z September DMSP visual imagery).

intensify, and by 050000Z had formed an eye (Figure 3-17-2). At that time, it was upgraded to typhoon intensity as it passed 130 nm (240 km) east of the islands of Tinian and Saipan in the Commonwealth of the Northern Marianas. The typhoon continued to track north-northwestward towards the axis of the subtropical ridge, and steadily intensified. During 7 September, Typhoon Ivy reached its maximum intensity of 115 kt (59 m/sec), then began to slow down as it made the turn around the ridge axis. Although the vertical shear increased, Ivy entrained most of its inflow from the warm, moist tropical air along its southeastern side. This factor, and its path right on top of the Kuroshio Current, resulted in a more gradual than normal decrease in intensity as the tropical cyclone accelerated south of Japan and transitioned to an extratropical low 600 nm (1110 km) east of Tokyo. The final warning was issued at 100600Z.

III. FORECAST PERFORMANCE

Initially, Ivy was on a westward course, then turned abruptly towards the north-northwest as it intensified. Before this turn, all JTWC forecasts reflected a west-northwest track under the subtropical ridge (Figure 3-17-3). On 3 September forecaster confidence was high that the ridge to the north of Ivy would hold and the track would be near Guam. Guam and Rota went into Condition of Readiness 2, as Ivy moved closer to the islands, and JTWC expected the system to reach typhoon intensity as it hit. The dynamic guidance was in agreement with the west-northwest track until the NOGAPS prognostic series at 040000Z. Then, the NOGAPS model indicated a rapid breakdown of the ridge, possibly in response to the southwesterly monsoon surge. Satellite data indicated that the tropical cyclone had turned, but an early radar fix still suggested west-northwestward motion. Once it was determined by subsequent radar information that Ivy was, in fact, moving away from the area, JTWC recommended that Tinian and Saipan increase their condition of readiness from 3 to 2. The Center then adopted a north-northwestward track that verified well as the system moved northward towards Japan.

The intensity forecasts for Ivy's early stages were initially too high due to a slower than normal rate of intensification. The forecast intensities verified well as the system recurved south of Japan.

IV. IMPACT

Rough seas churned up by Ivy's passage were responsible for one drowning on the island of Saipan. While Typhoon Ivy passed just to the east of Pagan (WMO 91222)(Figure 3-17-4) and Agrihan Islands in the Northern Marianas, no injuries and only minor damage were reported by the 13 residents of Agrihan. As Ivy paralleled the southern coast of Honshu, one fisherman was killed and four others were reported missing. Later, as the typhoon passed the southeastern tip of Honshu, Tokyo and the surrounding areas experienced high winds and heavy rains which disrupted ground and air transportation and left four people injured. Additional reports of damage in Japan included over 200 landslides and 733 flooded homes.

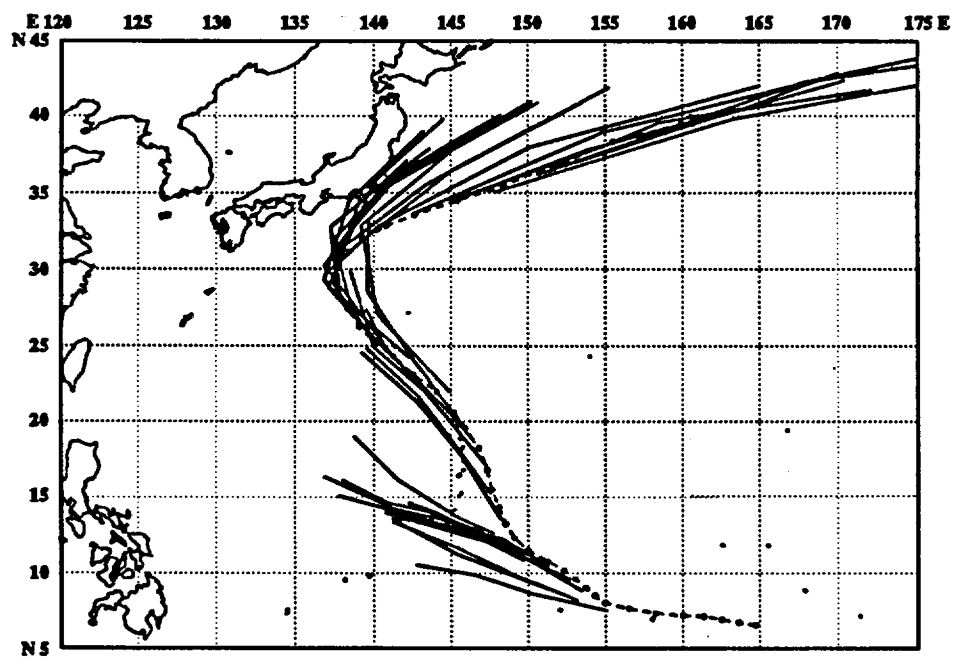


Figure 3-17-3. A comparison of JTWC official forecast positions with Ivy's verifying final best track positions.

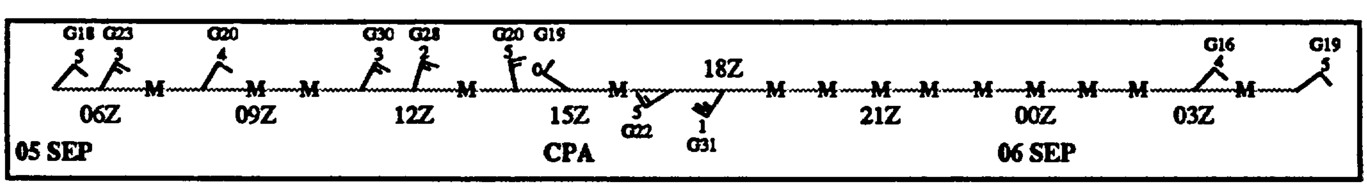
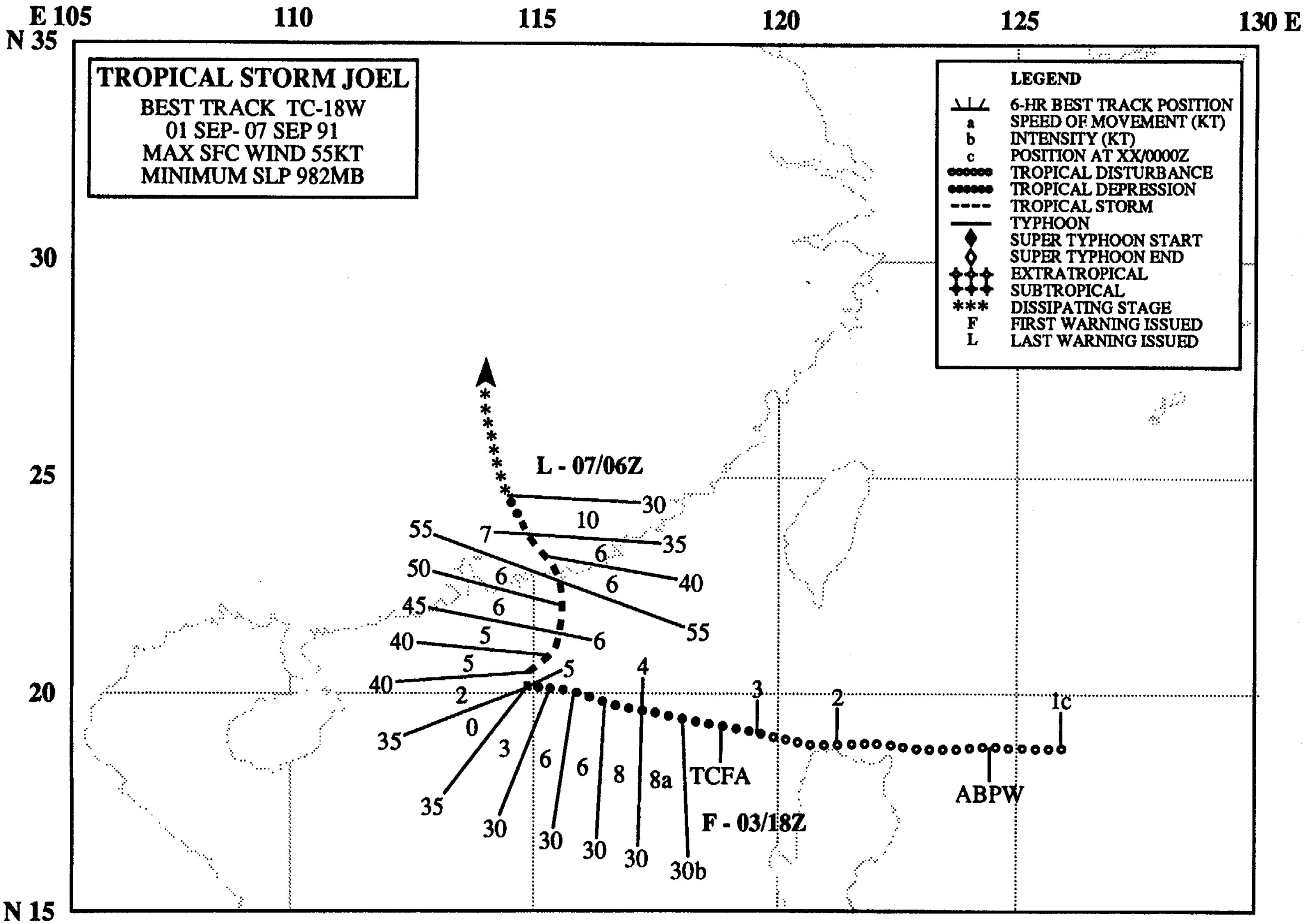


Figure 3-17-4. Intermittent wind reports from the Pagan Island (WMO 91222) Automatic Meteorological Observing Station reflect Ivy's passage to the east. The closest point of approach (CPA), 45 nm (85 km), occurred on 5 September.


TROPICAL STORM JOEL
BEST TRACK TC-18W
01 SEP- 07 SEP 91
MAX SFC WIND 55KT
MINIMUM SLP 982MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 105
110
115
120
125
130 E
N 35
30
25
20
N 15
L - 07/06Z
F - 03/18Z
TCFA
ABPW

TROPICAL STORM JOEL (18W)

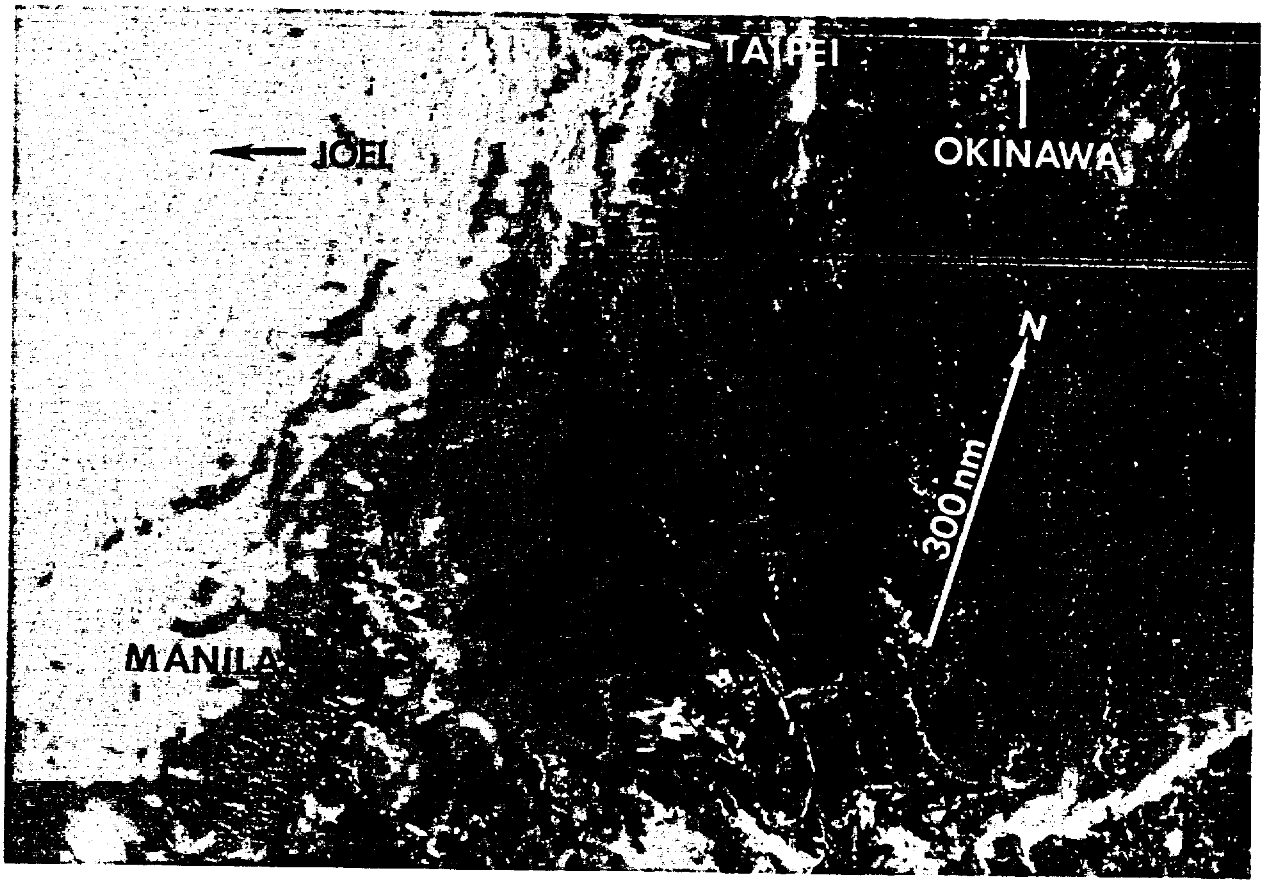
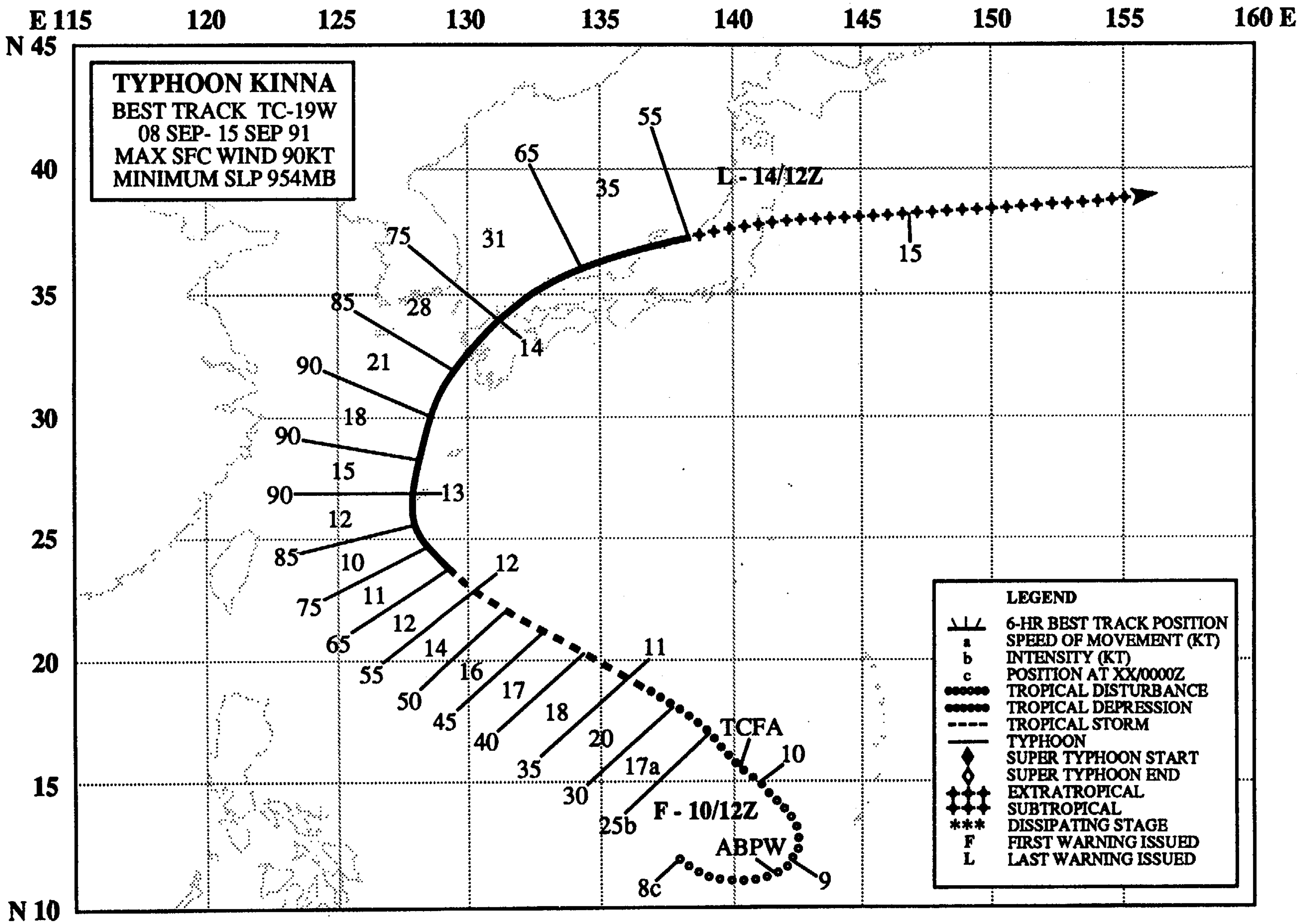


Figure 3-18-1 The cloud shield of Tropical Storm Joel covers much of the South China Sea just prior to landfall (060033Z September DMSP visual imagery).

Joel's poorly organized, but persistent, convection was first mentioned on the 010600Z September Significant Tropical Weather Advisory. Falling surface pressures along with increasing cloud amount and organization prompted a Tropical Cyclone Formation Alert at 030930Z. The first warning followed, valid at 031800Z. The subsequent upgrade to tropical storm intensity at 041200Z, appeared, in post analysis, to be 12 hours premature. As Joel tracked westward in the South China Sea, a southwesterly monsoon surge enhanced the deep convection near the cyclone's center. Then the surge, in conjunction with mid-tropospheric troughing to the north which interrupted the steering flow, caused Joel to come to a halt. After little or no movement for six hours, the tropical cyclone slowly moved northward towards the break in the ridge and made landfall at 161200Z, 70 nm (130 km) east of Hong Kong. Aided by convergent low-level wind flow in the coastal zone, Tropical Storm Joel reached its maximum intensity of 55 kt (28 m/sec) before moving onshore and dissipating over the mountains inland.


TYPHOON KINNA
BEST TRACK TC-19W
08 SEP- 15 SEP 91
MAX SFC WIND 90KT
MINIMUM SLP 954MB
E 115
120
125
130
135
140
145
150
155
160 E
N 45
40
35
30
25
20
15
N 10
L - 14/12Z
F - 10/12Z
TCFA
ABPW
LEGEND
6-HR BEST TRACK POSITION
SPEED OF MOVEMENT (KT)
INTENSITY (KT)
POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
FIRST WARNING ISSUED
LAST WARNING ISSUED

TYPHOON KINNA (19W)

I. HIGHLIGHTS

Kinna was the most destructive tropical cyclone to strike Okinawa since 1987, and the first typhoon to pass directly across the island since Vera in 1986. The typhoon also passed directly across Sasebo, Japan, and caused extensive damage on Kyushu and Honshu as it raced northeastward after recurvature. The exceptionally accurate forecasts of the path taken by Typhoon Kinna provided more than ample lead time for disaster preparation at key DOD installations.

II. TRACK AND INTENSITY

Kinna formed in the western Caroline Islands in the monsoon trough which extended across the Philippine Sea in early September. On 8 September, analysis of synoptic data revealed that a circulation was developing southwest of Guam. When satellite imagery showed an increase in convection near the circulation center, the Significant Tropical Weather Advisory was reissued at 081800Z to include the disturbance as an area with fair potential for tropical cyclone development. As the area of deep convection moved west of Guam and showed signs of increased organization, a Tropical Cyclone Formation Alert was issued at 100400Z. The first warning on Tropical Depression 19W was at 101200Z. Kinna's northwestward motion on 10 and 11 September was a reflection of a weak subtropical ridge north of the system which extended along 25°N latitude. The weak ridge allowed Kinna (Figure 3-19-1) to gain latitude as it intensified. At 120600Z, the presence of a poorly

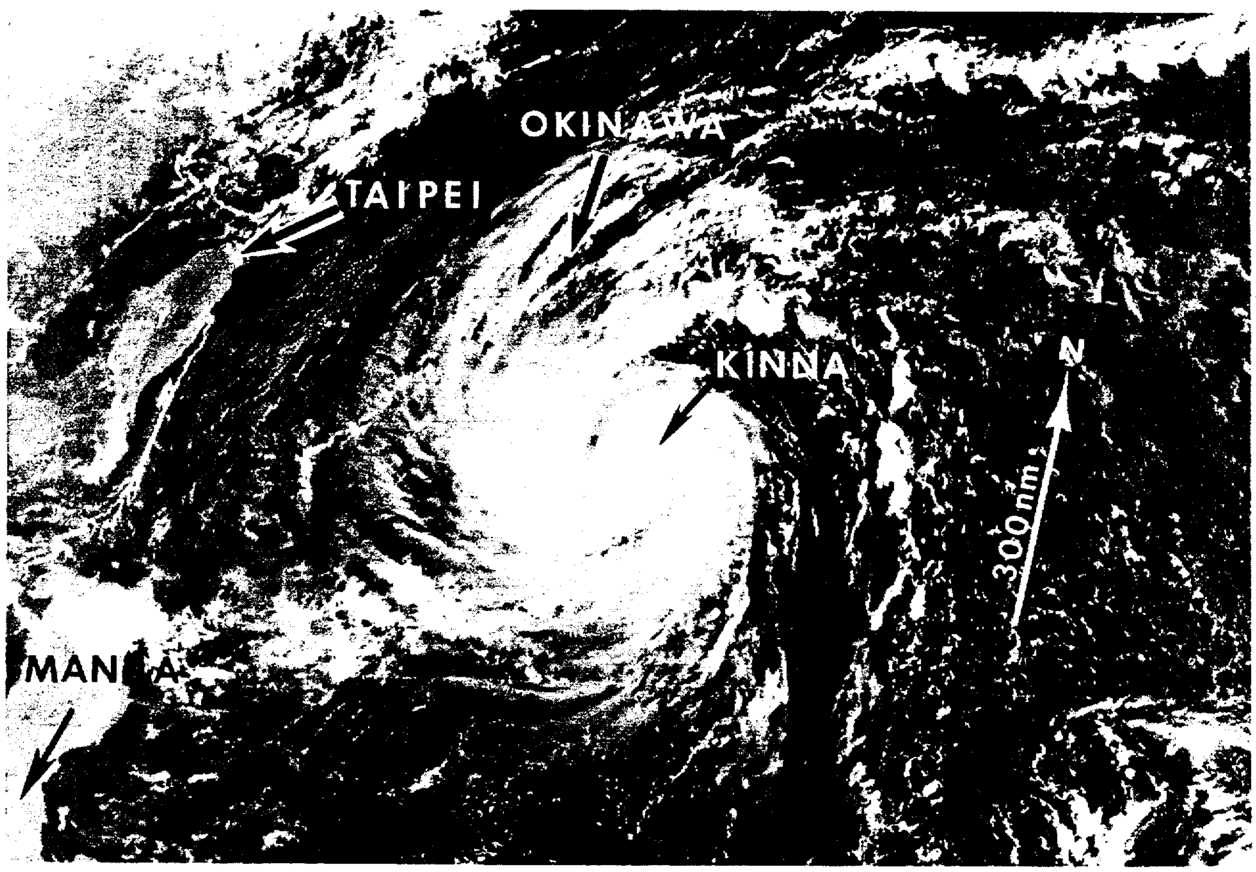


Figure 3-19-1. Typhoon Kinna intensifies as it heads for Okinawa, Japan (120004Z September DMSP visual imagery).

defined eye in the central dense overcast prompted an upgrade of Kinna to typhoon intensity.

On 12 September, a mid-tropospheric trough deepened in the East China Sea and split the weak ridge near 125°E longitude. In response, Typhoon Kinna turned northward toward the break in the ridge and tracked across Okinawa. The eye crossed densely populated southern Okinawa, with a minimum surface pressure of 958 mb recorded at Kadena AB (WMO 47931) (Figure 3-19-2). The wind recorder chart from Futenma MCAS (WMO 47933) graphically describes the three hour passage of the eye across the station (Figure 3-19-3). On Okinawa, the peak wind gust observed at Futenma MCAS (WMO 47933) was 96 kt (49 m/sec) with 82 kt (42 m/sec) at Kadena AB, and 95 kt (49 m/sec) at Naha. After recurvature, Kinna accelerated north-northeastward toward Kyushu and maintained its intensity. It's eye wall passed over the cities of Nagasaki and Sasebo on Kyushu on the 13th, with peak wind gusts of 100 kt (51 m/sec) recorded at Metabaru (WMO 47860), located 45 nm (85 km) northeast of Nagasaki. Kinna continued to accelerate due to deep mid-tropospheric westerly flow, and rapidly transitioned into an extratropical low as it tracked along the northern coast of Honshu. The final warning was issued at 141200Z.

III. FORECAST PERFORMANCE

After opting for a recurvature track on the third warning at 111800Z, forecasters correctly identified the major changes that would occur in the subtropical ridge as the short wave trough moved off of Asia. JTWC forecasters accurately predicted that Kinna would strike Okinawa, Sasebo (on Kyushu), and later skirt the northern coast of Honshu. Starting with the fourth warning issued at 120000Z, JTWC stayed with this forecast track (Figure 3-19-4). As a consequence, JTWC's performance was substantially better than its objective aids, primarily because the forecast guidance was much slower than Kinna's actual forward motion. Forecasters relied heavily on persistence for speed guidance as Kinna approached the point of recurvature and then began to accelerate. Although JTWC had a good handle on the path the typhoon would take, the greatest forecast problem was the amount of acceleration to expect as Kinna underwent extratropical transition.

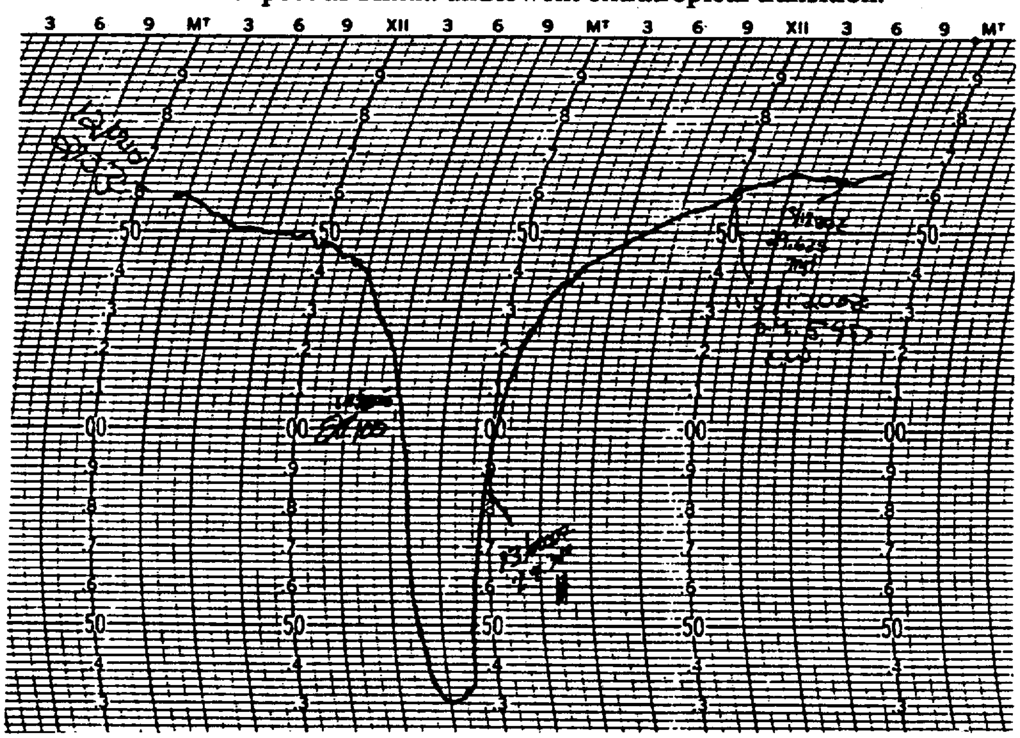


Figure 3-19-2. Microbarograph trace of surface pressure in inches of mercury recorded at Kadena AB, Japan during Kinna's passage. The minimum 28.30 at 122100Z September equates to 958 mb.

IV. IMPACT

As a result of the accurate warnings, preparations to limit the amount of damage on Okinawa and to sortie ships in the path of the typhoon were made well in advance of Kinna's approach. Despite the strong winds, damage to military installations on Okinawa and at Sasebo was minimal. Nine deaths and 65 injuries were attributed to Typhoon Kinna in Japan and on Okinawa. Most of the damage occurred on Kyushu near Nagasaki and on western Honshu. Press reports indicated 158 houses collapsed, more than 2,733 were flooded, and nearly 500,000 households were without power. The eight inches of rain which fell on Okinawa in a 24-hour period during Kinna's passage eased the island's drought conditions, and temporarily eliminated water rationing.

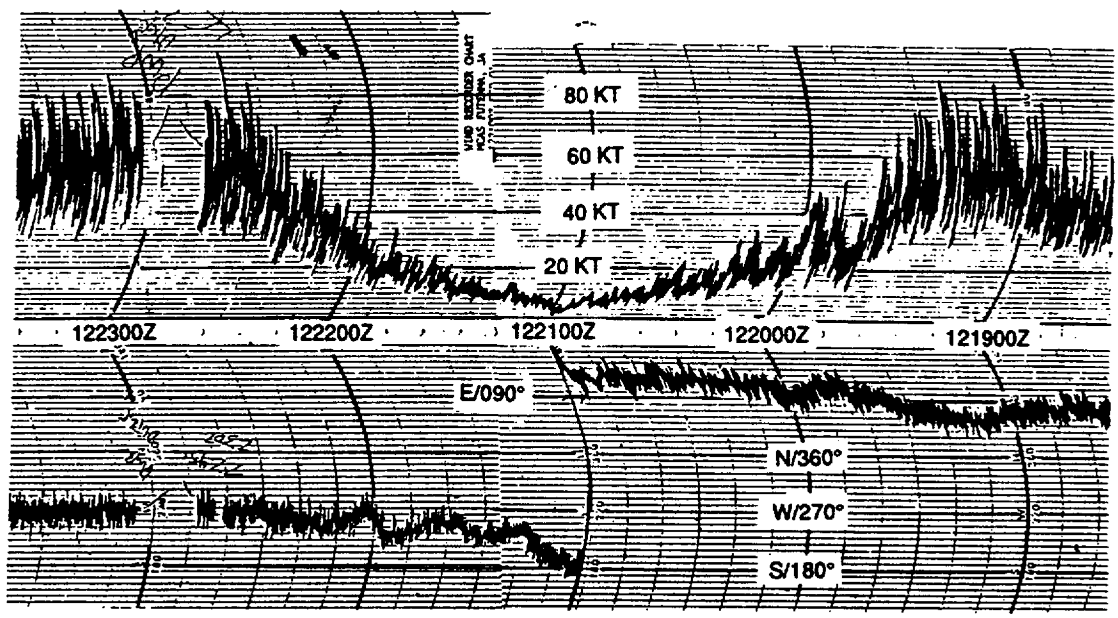


Figure 3-19-3. Futenma MCAS (WMO 47933), Okinawa, Japan, wind recorder chart reflects the three hour passage of Kinna's eye across the station.

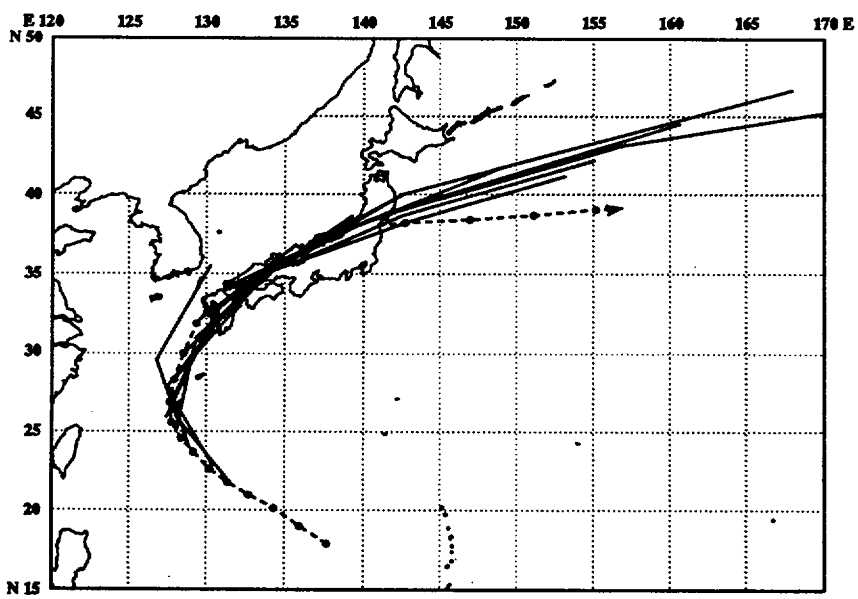
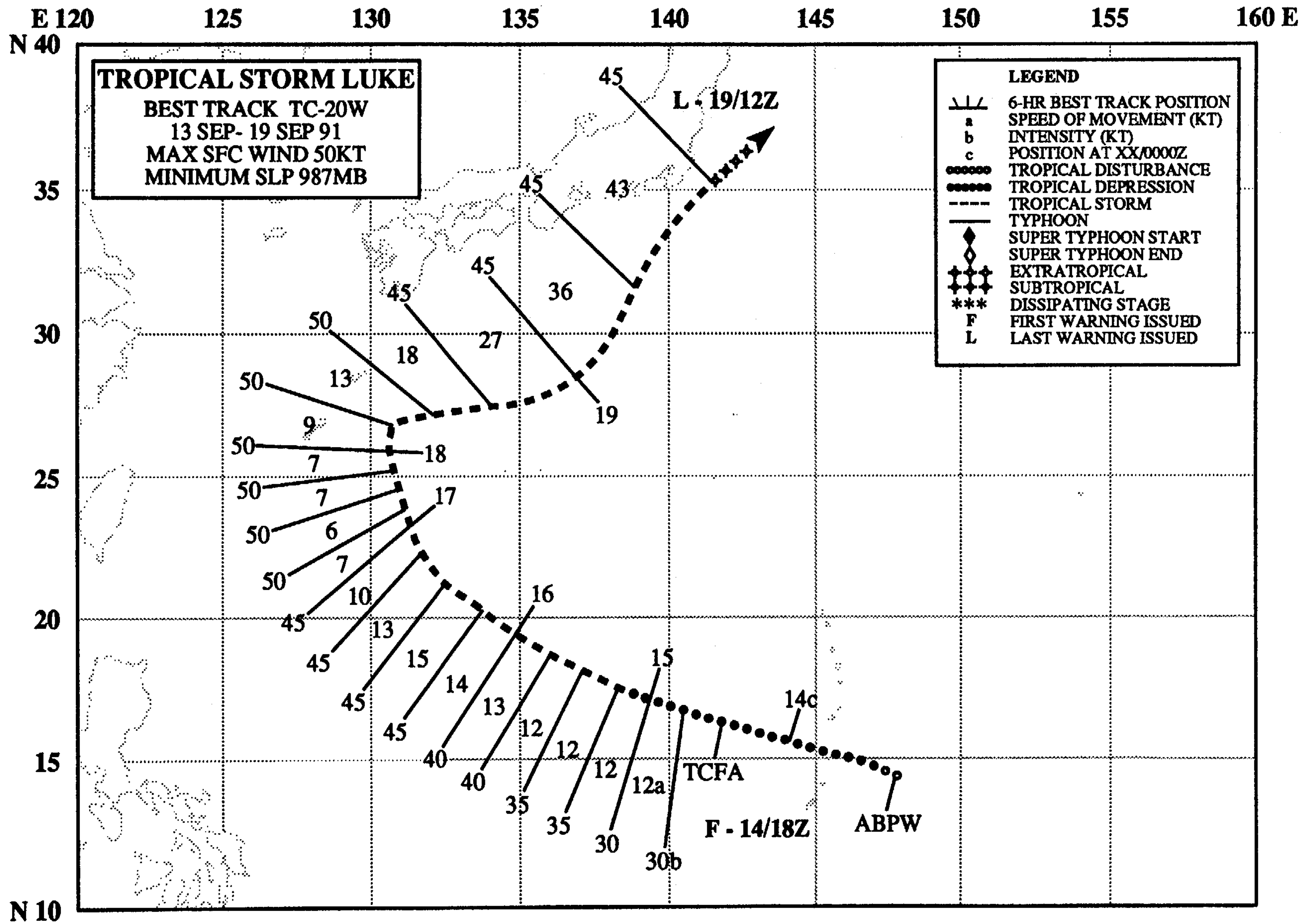


Figure 3-19-4. Comparison of JTWC forecasts issued from 120000Z to 140000Z September to the best track of Typhoon Kinna. JTWC forecasts correctly predicted the eventual path of Kinna, but were slow to predict Kinna's acceleration across Japan.


TROPICAL STORM LUKE
BEST TRACK TC-20W
13 SEP- 19 SEP 91
MAX SFC WIND 50KT
MINIMUM SLP 987MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 120
125
130
135
140
145
150
155
160 E
N 40
35
30
25
20
15
N 10
L - 19/12Z
F - 14/18Z
TCFA
ABPW
14c
12a
30b

TROPICAL STORM LUKE (20W)

I. HIGHLIGHTS

Tropical Storm Luke (20W), a broad monsoonal cyclone, had the largest initial position errors of the season. Its unusual recurvature track was the result of an extension of the mid-latitude westerlies deep into the tropics in mid-September, which temporarily broke down the subtropical ridge in the western Pacific.

II. TRACK AND INTENSITY

Luke formed from a disturbance that passed near Saipan late on 14 September. It was initially mentioned on the 130600Z Significant Tropical Weather Advisory. As the disturbance tracked west-northwestward, improved upper-level anticyclonic outflow and sea-level pressure falls of 3 mb led to the issuance of a Tropical Cyclone Formation Alert at 141130Z. At 141800Z, the first warning on Tropical Depression 20W was issued when the synoptic data indicated that a closed circulation had developed. At this time, Luke was a monsoon depression, with a ring of 30 kt (15 m/sec) winds around a large central area of light and variable winds. The cyclone continued to slowly intensify over the next 48 hours as it tracked west-northwestward. On 17 September, satellite imagery indicated that the circulation had lost organization, and that it appeared to be moving westward, but on 18 September an exposed low-level circulation revealed that the tropical storm had, in fact, turned north-northwestward (Figure 3-20-1). Shortly afterward, Luke made another sharp change in direction to the east as a mid-tropospheric trough brought westerly winds deep into the tropics and caused the subtropical ridge,

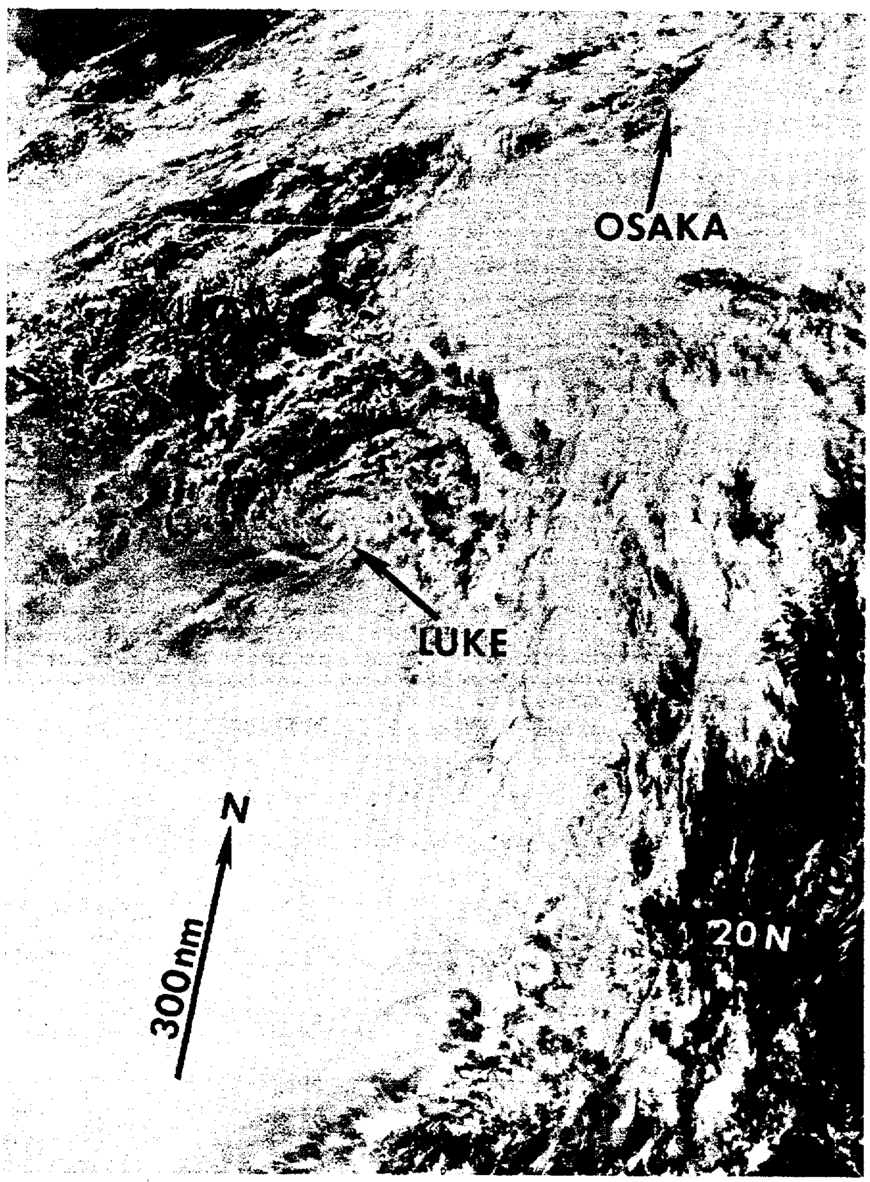
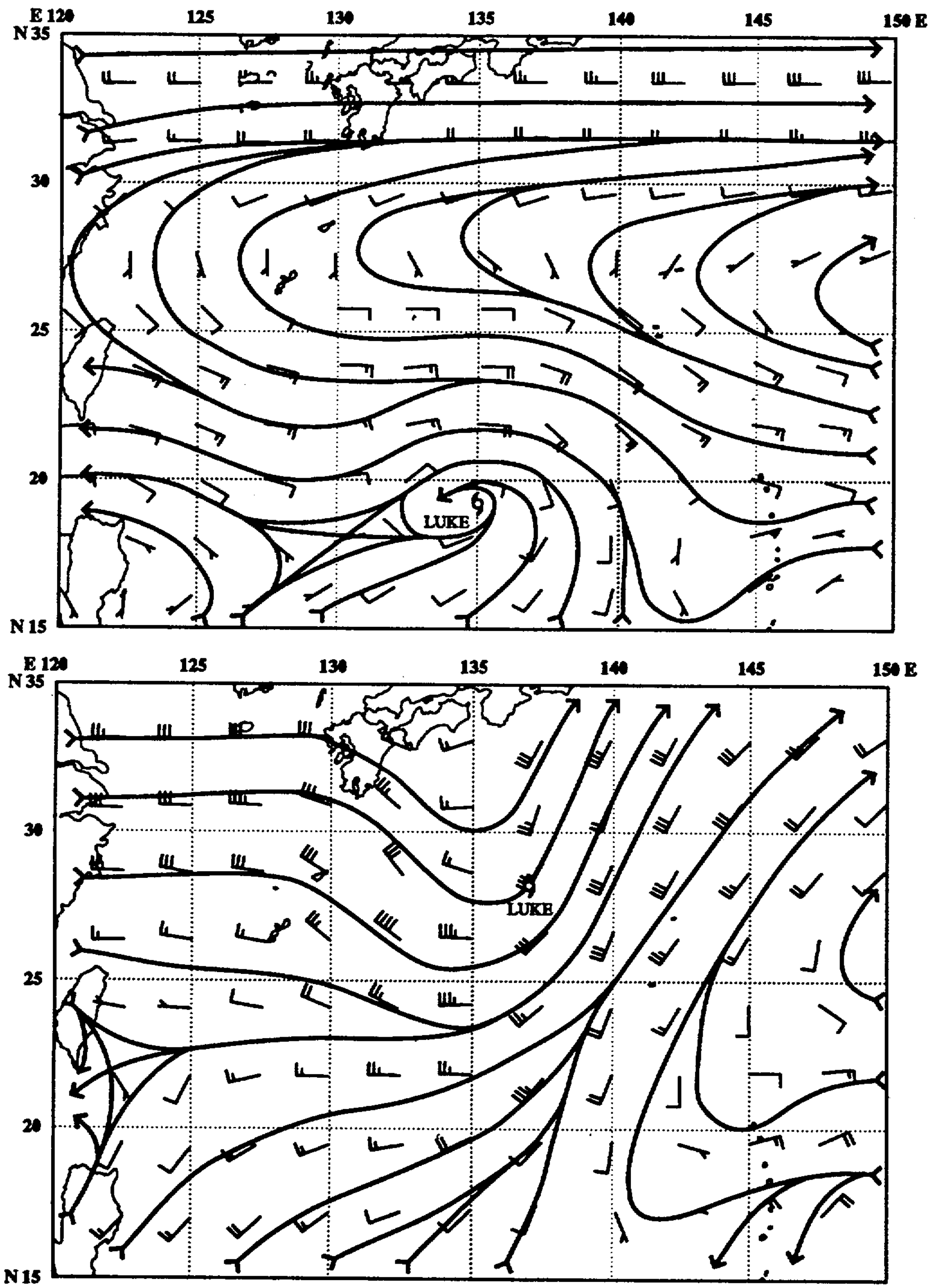


Figure 3-20-1. The exposed low-level center of Tropical Storm Luke as it makes its closest point of approach 160 nm (295 km) east of Okinawa (172336Z September DMSP visual imagery).

which had been holding the system to a westward track, to recede eastward (Figure 3-20-2). Meanwhile, the vertical wind shear between Luke and the westerlies scrambled the cloud pattern during the evening hours. This left JTWC attempting to extrapolate a track to the north-northwest, while the obscured low-level circulation of Luke (Figure 3-20-3) was actually accelerating northeastward and transitioning into an extratropical cyclone. This misinterpretation caused JTWC forecasters to issue an unnecessary Tropical Cyclone Formation Alert at 181500Z on a peripheral convective area. The alert was canceled at 190400Z. The final warning on Tropical Storm Luke was issued at 191200Z.

III. FORECAST PERFORMANCE



(a)

(b)

Figure 3-20-2. NOGAPS Deep-layer mean analyses at (a) 160000Z and (b) 190000Z September. Note the dramatic change in the extent of the subtropical ridge axis during the 72-hour period as mid-latitude westerlies associated with a passing trough penetrated unusually far equatorward.

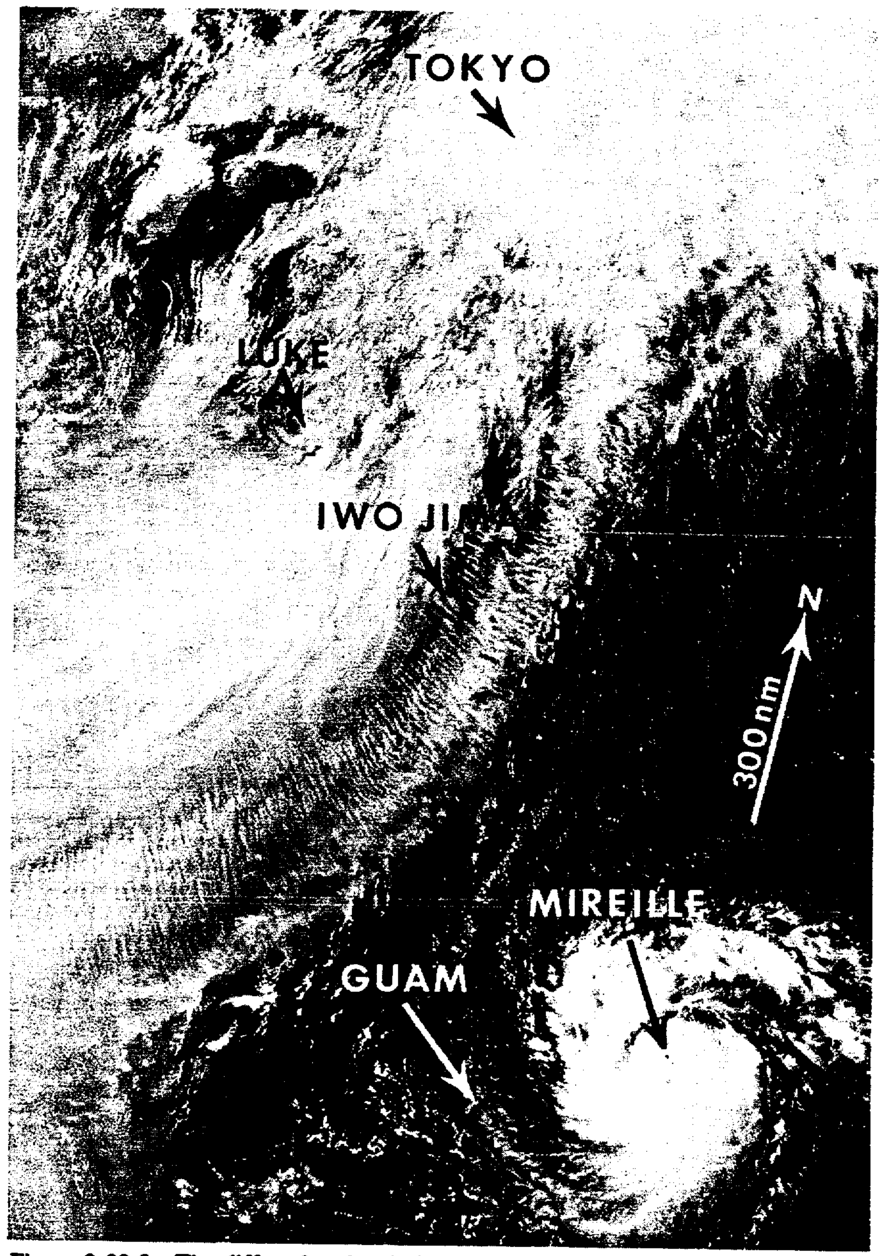
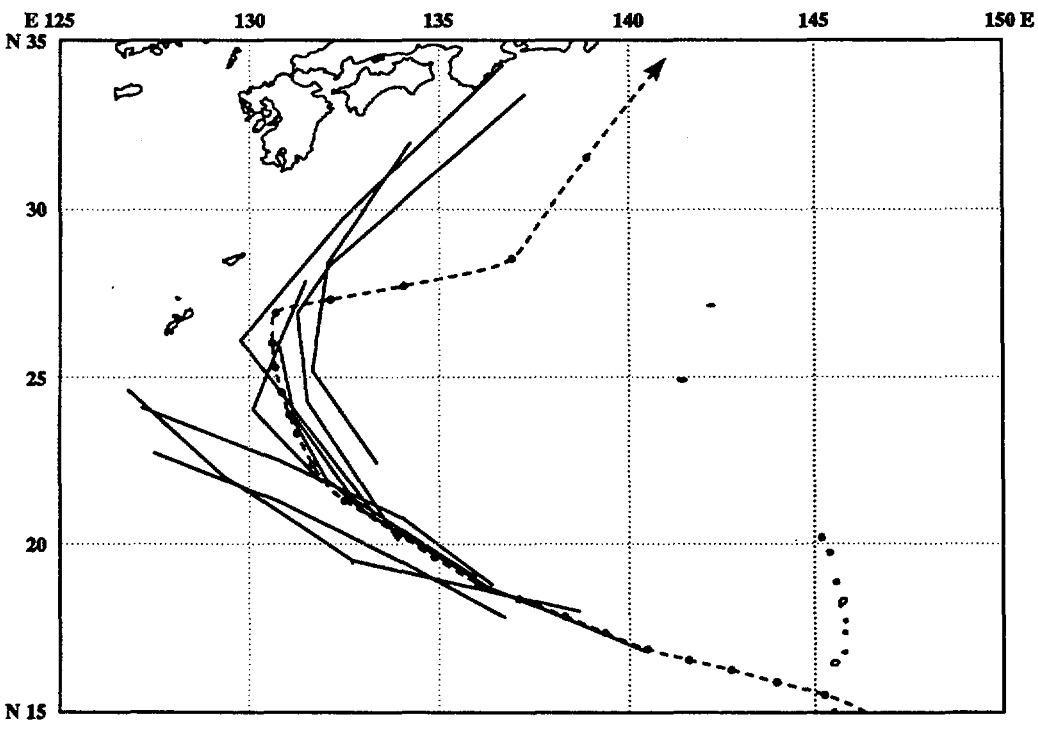


Figure 3-20-3. The diffuse low-level circulation and extensive area of convection associated with Luke as it undergoes extratropical transition south of Honshu. Typhoon Mireille (21W) appears at the lower right of the picture (182314Z September DMSP visual imagery).

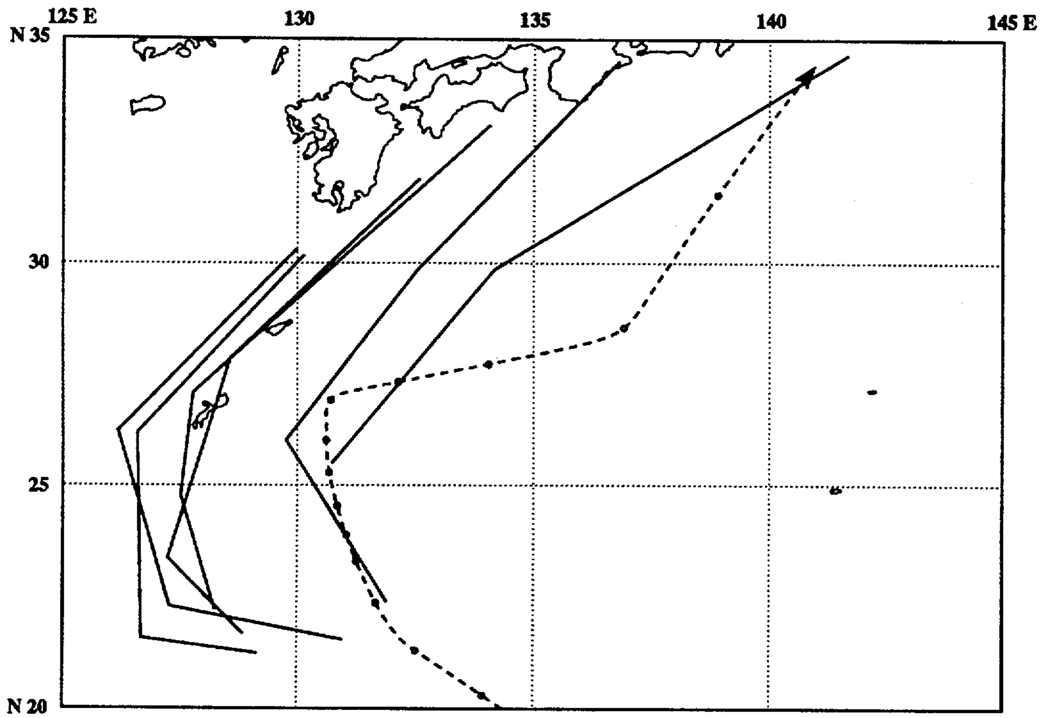
On 17 and 18 September, uncertainty over the initial warning positions of Tropical Storm Luke underscored the limitations that can occur in locating a poorly defined cloud system center from only infrared satellite images, and the effect these limitations can have on JTWC warnings. A comparison of JTWC forecasts with the verifying best track graphically illustrates where erroneous initial positions misled JTWC forecasts (Figure 3-20-4). Until 161800Z, JTWC warnings were in agreement that Luke would recurve east of Okinawa and head toward Honshu ahead of an approaching mid-tropospheric trough. These warnings accurately represented the future path of the cyclone and had low forecast errors. Starting at 170000Z, forecasters adopted the scenario that the system was moving westward, causing the recurvature forecast tracks to be adjusted further westward, threatening Okinawa. A relocation of the warning position at 180000Z was too late to prevent the evacuation of some aircraft from Kadena AB on Okinawa. Another major relocation of the cyclone occurred at 190000Z because of the significant track change which occurred during the nighttime. Using infrared imagery, satellite analysts had a challenging task locating the poorly defined circulation center residing beneath a dense cloud shield. In turn, JTWC's extrapolation of the perceived short-term motion resulted in large forecast errors.

IV. IMPACT

Although Luke did not attain typhoon intensity, its broad area of gale-force winds and torrential rains affected large portions of the western Pacific. On 17 September, JTWC forecasts resulted in the unnecessary evacuation of aircraft stationed at Kadena AB, costing an estimated $300,000. Later, on 19 September, record rainfall from Luke caused extensive flooding in central Japan, resulting in the deaths of at least 8, with 10 other people reported missing and damage to 28,000 homes.



(a)



(b)

(c)

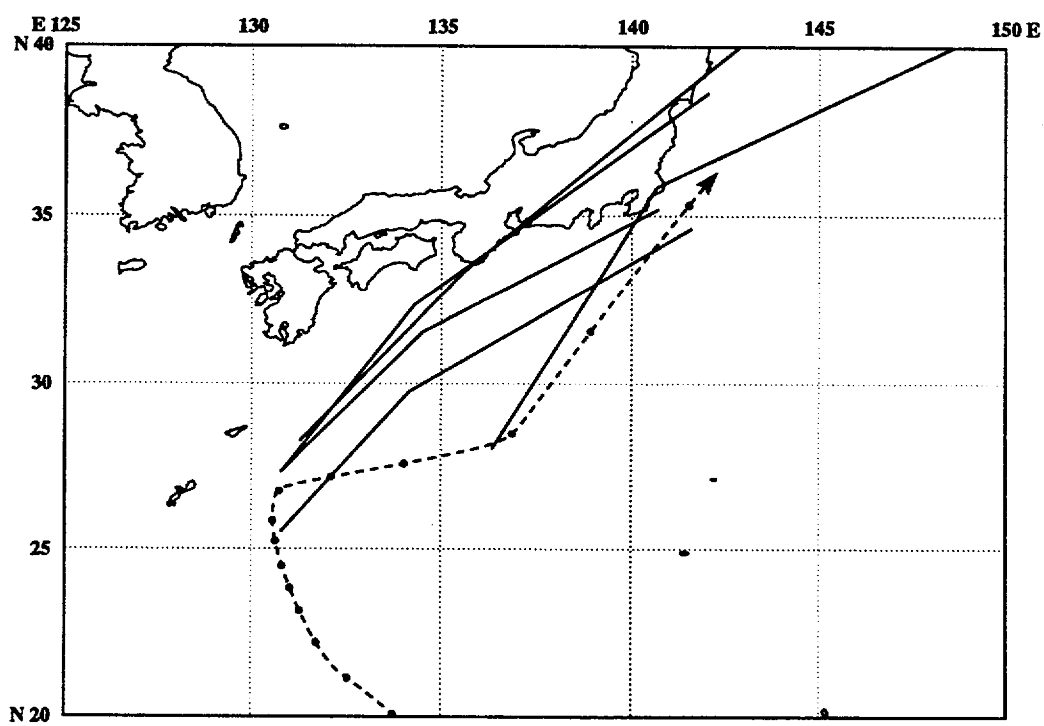
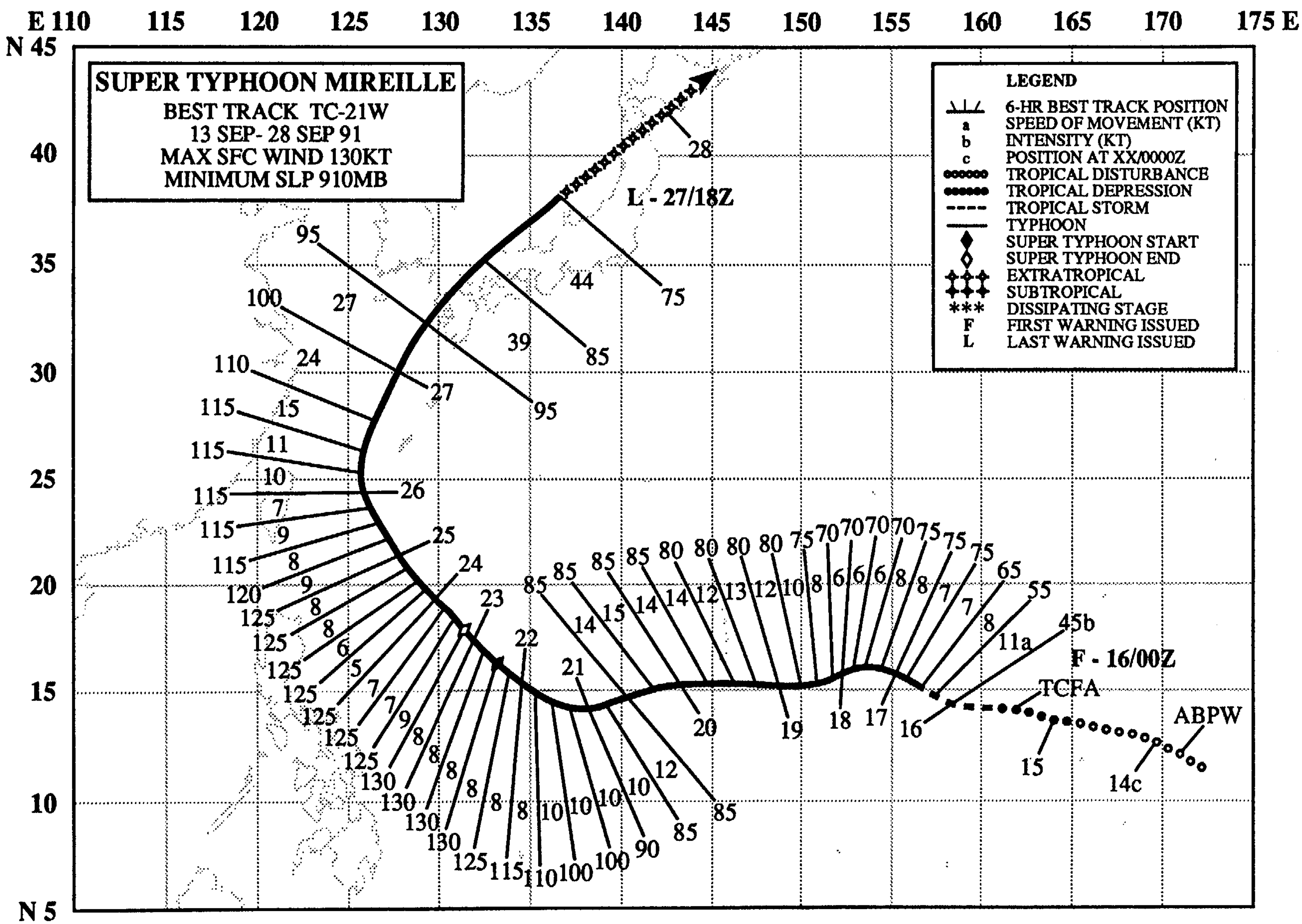


Figure 3-20-4. Comparison of the oficial forecast to the final best track for (a) 141800Z to 161800Z, (b) 161800Z to 180000Z, and (c) 180600Z to 190000Z September.


SUPER TYPHOON MIREILLE
BEST TRACK TC-21W
13 SEP- 28 SEP 91
MAX SFC WIND 130KT
MINIMUM SLP 910MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 110
115
120
125
130
135
140
145
150
155
160
165
170
175 E
N 45
40
35
30
25
20
15
10
N 5
L - 27/18Z
F - 16/00Z
TCFA
ABPW

SUPER TYPHOON MIREILLE (21W)

I. HIGHLIGHTS

The second super typhoon in the Northwest Pacific of the year, Mireille became the worst storm to strike Japan in three decades. Mireille outgrew its early midget size and reached super typhoon intensity several days before threatening Okinawa. Recurving just to the southwest of Okinawa, the typhoon accelerated, cutting a path across western Kyushu and Honshu. Then over the Sea of Japan, Mireille transitioned into an intense extratropical cyclone which slammed into northern Honshu. Mireille was part of a three storm outbreak in September - first with Tropical Storm Luke (20W) and Typhoon Nat (22W), and later with Typhoons Nat and Orchid (23W).

II. TRACK AND INTENSITY

Mireille was first detected as a poorly organized area of cloudiness in the monsoon trough over the southern Marshall Islands. The disturbance was first mentioned on the 130600Z Significant Tropical Weather Advisory. An increase in the amount of the tropical disturbance's deep convection prompted a Tropical Cyclone Formation Alert at 151200Z. Assuming normal development, forecasters issued the first warning for a 30 kt (15 m/sec) system at 160000Z. However, this was not to be a normal system. This was reflected in the 160600Z warning which upgraded the intensity to 45 kt (23 m/sec) and identified the system as very compact and rapidly intensifying. For several days the tropical system drifted to the west-northwest under the influence of the subtropical ridge. On the evening of 17 September, Mireille began to track to the west-southwest, creating some concern that it would target Guam, but 24 hours later the typhoon acquired a westward track and passed 12 nm (20 km) north of Saipan on 19 September as a midget typhoon. Then, on 21 September, the typhoon (Figure 3-21-1) began tracking to the northwest along the southwestern periphery of the ridge, and began interacting with Typhoon Nat (22W). This binary interaction (Figure 3-21-2) resulted in the temporary capture of the smaller typhoon, Nat, and its subsequent movement southward in the South China Sea. After releasing Nat, Mireille recurved under increasing southwesterly mid-tropospheric winds, and accelerated northeastward past Okinawa. Extratropical transition occurred in the Sea of Japan and the intense baroclinic storm continued northeastward, first passing over the extreme northern section of Honshu and then moving over southern Hokkaido.

The tropical cyclone initially peaked at 75 kt (39 m/sec) on 16 September and remained at moderate typhoon intensity until 21 September when it commenced a second deepening episode enroute to super typhoon intensity. This second episode was associated with decreasing upper-level wind shear from Tropical Storm Luke (20W) as that system weakened and accelerated northward. After peaking at 130 kt (65 m/sec) for a day (221200Z to 230600Z), Mireille began to slowly weaken.

Mireille's size, which was determined by the diameter of its outer-most closed isobar, began to gradually increase after an intensity of 80 kt (40 m/sec) was reached, and continued through extratropical transition.

III. FORECAST PERFORMANCE

As Mireille passed the Mariana Islands, it was difficult to determine how much the thin extension of the subtropical ridge would affect the cyclone's track. The first indications of a possible west-southwestward track excursion toward Guam came from the Beta Advection Models. OTCM also locked onto a west-southwest track after the turn had started. However, both FBAM and OTCM overemphasized the southward excursion which lasted only a day.

After the system had passed the Marianas, recurvature forecasts were premature. The NOGAPS model underestimated the strength and duration of the subtropical ridge, and as a result all of the dynamic objective aids indicated early recurvature. The underestimation may have been the model's response to receiving three simultaneous tropical cyclone boguses in the basin corresponding to three storms. Also, the bogus, initializing the NOGAPS model, overplayed the size of Mireille, which in turn overemphasized the storm's weakening influence on the ridge.

IV. IMPACT

As Mireille approached the Mariana Islands, the wobble of its track and subsequent adjustment of the forecast to the north and back to the west, resulted in a flurry of disaster preparedness preparations on Guam northward through Saipan. When the midget typhoon passed north of Saipan, no reports of deaths or injuries were received. However, the island did suffer 70-80% crop damage, in addition to trees being uprooted, and coral roads seriously eroded. Most damage was confined to the north end of the island. Okinawa experienced 27 hours with winds greater than 50 kt (25 m/sec) and Kadena AB recorded a peak gust of 82 kt (41 m/sec). The island also recorded a total rainfall of 10.14 inches, and as a result, was able to cancel water rationing for the remainder of the

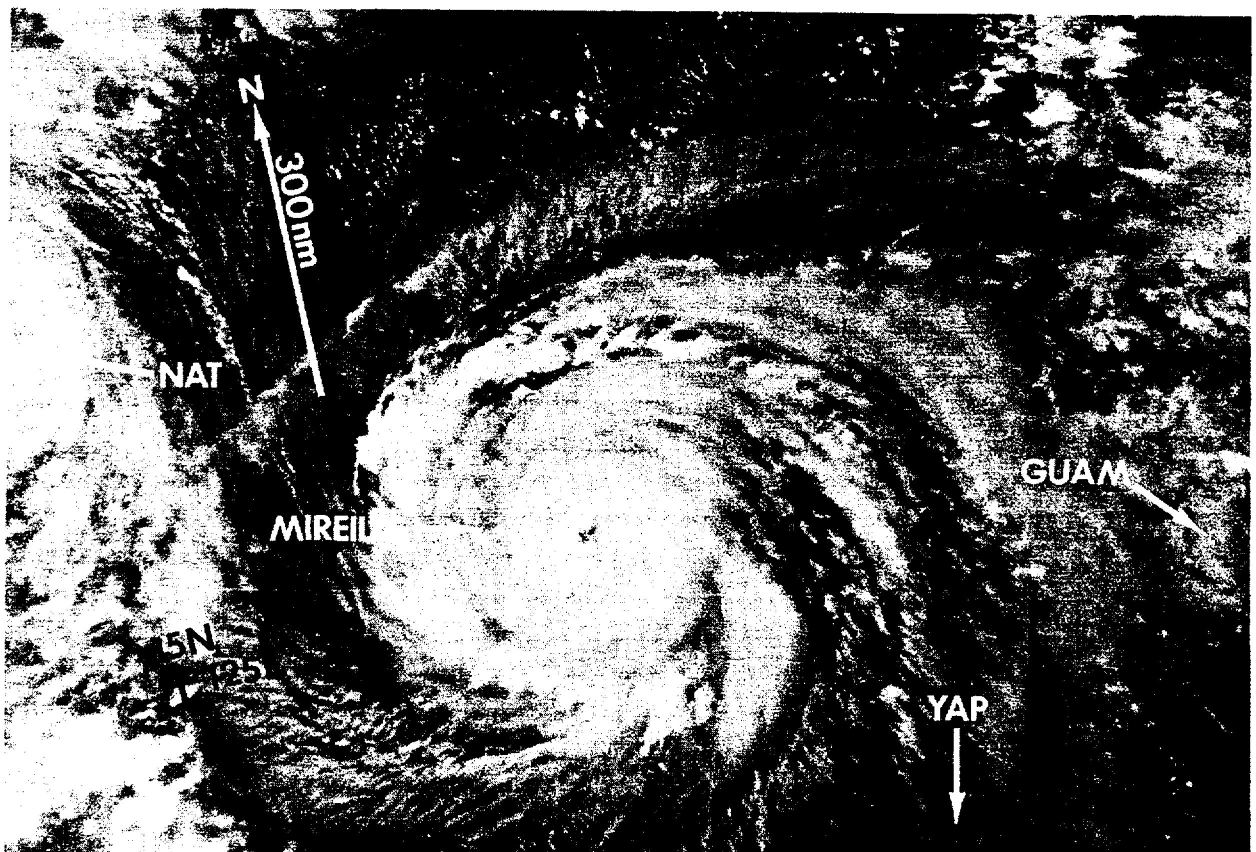


Figure 3-21-1. Moonlight view of Typhoon Mireille. A portion of Typhoon Nat's (22W) cloud shield can be see along the extreme left edge of the picture (221230Z September DMSP visual imagery).

year. Press reports from Japan indicated that 52 deaths were associated with the typhoon, including all ten crew members of a South Korean freighter that capsized while in port at Hakata on the island of Kyushu. Press reports also indicated 777 injuries, the flooding of approximately 10,000 homes, and power outages affecting nearly 6 million homes. Japanese crop damage was estimated at US$3 billion, with the apple crop being particularly hard hit. Nagasaki (WMO 47855) reported winds of 72 kt (37 m/sec) gusting to 118 kt (61 m/sec). On northern Honshu, Misawa AB recorded the most destructive winds since the U.S. started record-keeping for the base in 1946. For more than 5 hours the winds were 50 kt (25 m/sec) or greater and included a peak gust to 82 kt (41 m/sec). The previous all-time record for the base was 70 kt (35 m/sec) in March of 1987. The resulting wind damage was estimated to be between $0.5 to $1.5 million dollars. Several warehouse roofs were torn off, storage sheds were reportedly knocked off their foundations, and trees were blown down. The *Pacific Stars and Stripes* reported: "Base officials credit the Joint Typhoon Warning Center in Guam with early storm forecasts that allowed them to warn the base population and get million-dollar aircraft into hardened shelters."

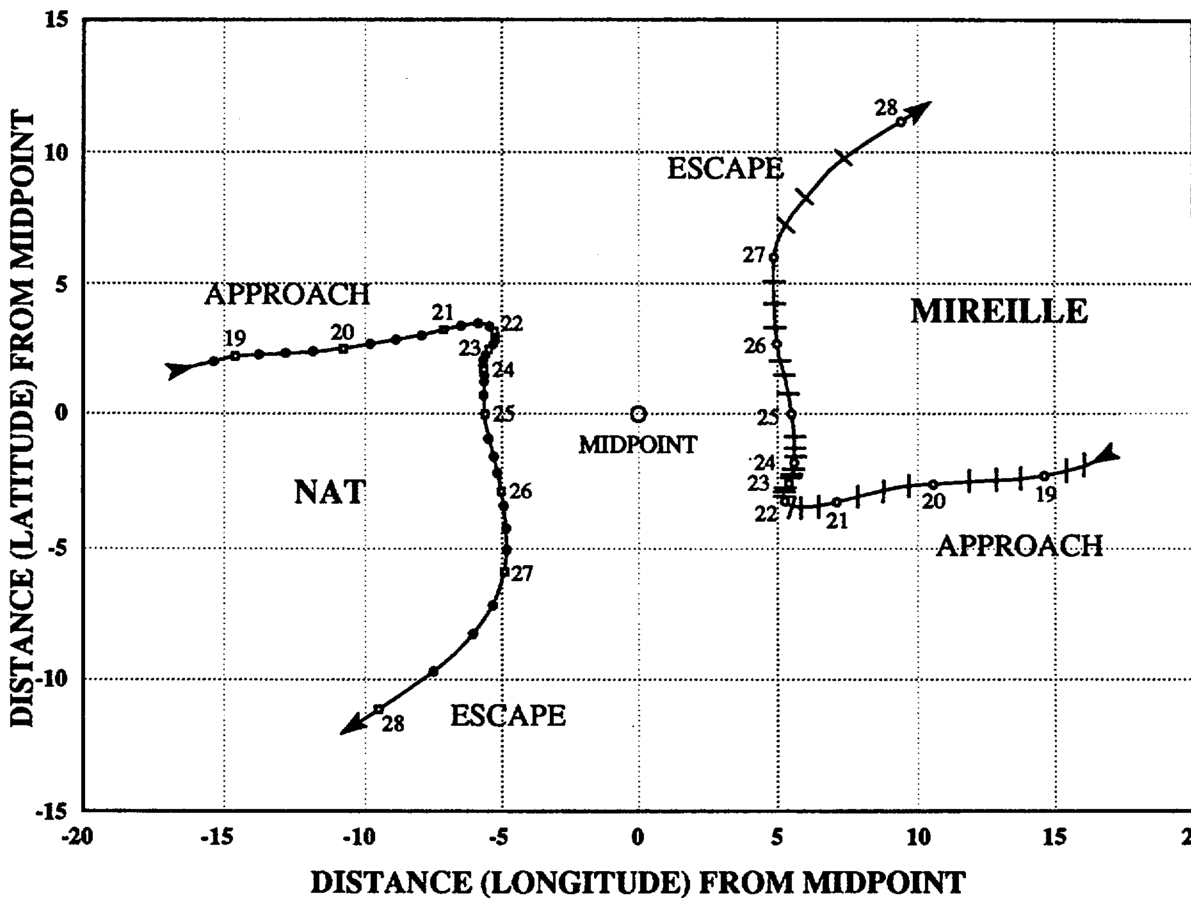
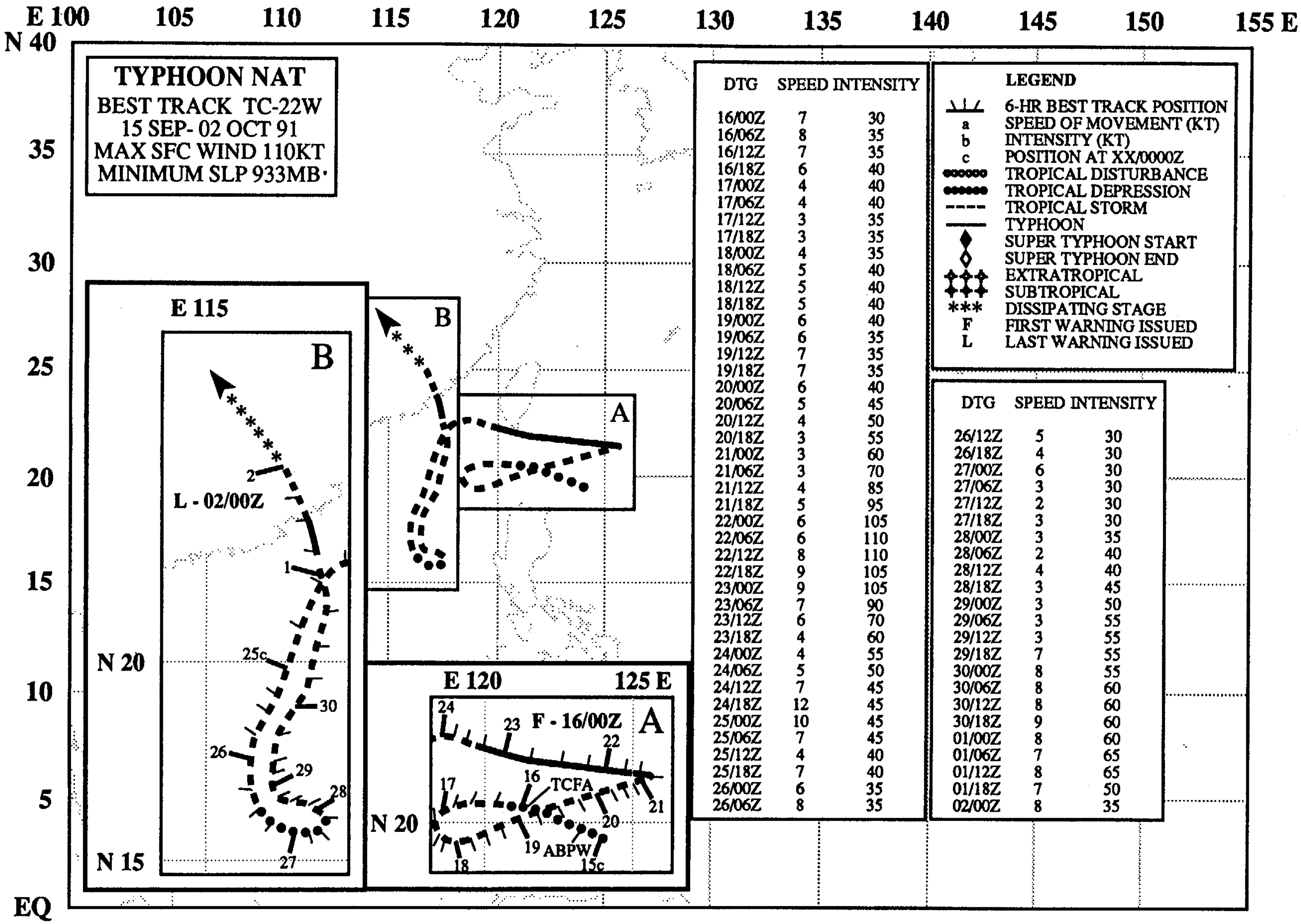


Figure 3-21-2. A plot of 6-hourly positions relative to the common midpoint shows the binary interaction between Typhoons Mireille and Nat (22W).

TYPHOON NAT

BEST TRACK TC-22W
15 SEP- 02 OCT 91
MAX SFC WIND 110KT
MINIMUM SLP 933MB



LEGEND

6-HR BEST TRACK POSITION	
a	SPEED OF MOVEMENT (KT)
b	INTENSITY (KT)
c	POSITION AT XX/0000Z
	TROPICAL DISTURBANCE
	TROPICAL DEPRESSION
	TROPICAL STORM
	TYPHOON
	SUPER TYPHOON START
	SUPER TYPHOON END
	EXTRATROPICAL
	SUBTROPICAL
***	DISSIPATING STAGE
F	FIRST WARNING ISSUED
L	LAST WARNING ISSUED

DTG	SPEED	INTENSITY
16/00Z	7	30
16/06Z	8	35
16/12Z	7	35
16/18Z	6	40
17/00Z	4	40
17/06Z	4	40
17/12Z	3	35
17/18Z	3	35
18/00Z	4	35
18/06Z	5	40
18/12Z	5	40
18/18Z	5	40
19/00Z	6	40
19/06Z	6	35
19/12Z	7	35
19/18Z	7	35
20/00Z	6	40
20/06Z	5	45
20/12Z	4	50
20/18Z	3	55
21/00Z	3	60
21/06Z	3	70
21/12Z	4	85
21/18Z	5	95
22/00Z	6	105
22/06Z	6	110
22/12Z	8	110
22/18Z	9	105
23/00Z	9	105
23/06Z	7	90
23/12Z	6	70
23/18Z	4	60
24/00Z	4	55
24/06Z	5	50
24/12Z	7	45
24/18Z	12	45
25/00Z	10	45
25/06Z	7	45
25/12Z	4	40
25/18Z	7	40
26/00Z	6	35
26/06Z	8	35

DTG	SPEED	INTENSITY
26/12Z	5	30
26/18Z	4	30
27/00Z	6	30
27/06Z	3	30
27/12Z	2	30
27/18Z	3	30
28/00Z	3	35
28/06Z	2	40
28/12Z	4	40
28/18Z	3	45
29/00Z	3	50
29/06Z	3	55
29/12Z	3	55
29/18Z	7	55
30/00Z	8	55
30/06Z	8	60
30/12Z	8	60
30/18Z	9	60
01/00Z	8	60
01/06Z	7	65
01/12Z	8	65
01/18Z	7	50
02/00Z	8	35

TYPHOON NAT (22W)

I. HIGHLIGHTS

Typhoon Nat's motion was highly erratic and included four major track changes, two intensification episodes, and two landfalls in 17 days. It persisted longer than any other tropical cyclone that formed in the western North Pacific during 1991, requiring a total of 61 warnings which was only 18 warnings shy of the record set by Typhoon Rita (1972). Its track and behavior was reminiscent of Typhoon Wayne (1986).

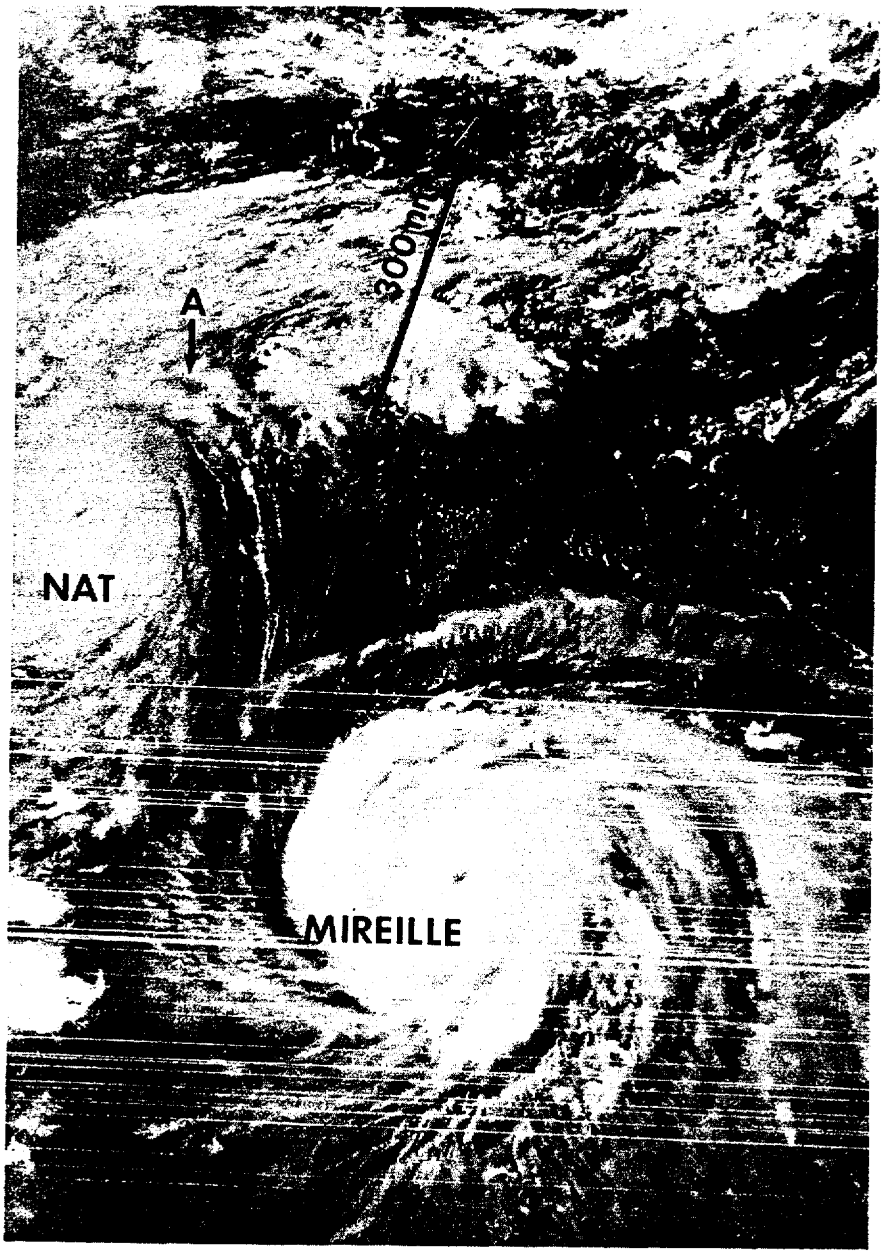


Figure 3-22-1. Moonlight imagery reveals the eyes of Typhoons Nat and Mireille (21W). Lightning flashes can be seen east of Taiwan near point A (221059Z September DMSP visual imagery).

II. TRACK AND INTENSITY

Nat's convection developed in the monsoon trough just east of the Luzon Strait and was first mentioned on the 150600Z Significant Tropical Weather Advisory. At 152300Z, improved cloud organization prompted a Tropical Cyclone Formation Alert. The alert was followed only an hour later by the first warning based on a 27 kt (14 m/sec) synoptic report and an estimated minimum sea-level pressure of 1003 mb. Nat initially intensified very slowly due to its proximity to land and to strong upper-level winds outflowing from Tropical Storm Luke (20W) which was located to the east. The influence of these two factors lessened after a surge in the southwest monsoon carried Nat to the east through the Luzon Strait, and Luke recurved. From 21 through 22 September, Nat underwent rapid deepening to almost super typhoon intensity. After Luke's departure, the ridge re-established itself and Nat (Figure 3-22-1 and 3-22-2) reversed direction to enter the Luzon Strait again. Nat made landfall (Figure 3-22-3) on the southern tip of Taiwan and rapidly weakened. Contributing factors to the weakening were the proximity of the high mountains of Taiwan and the approach of Typhoon Mireille (21W) from the southeast with its outflow causing increased upper-level wind shear. During the binary interaction with Mireille (See Figure 3-21-2 in Mireille's write-up), Nat was downgraded to a tropical depression before the larger system, Mireille, escaped northeastward. Nat reintensified to typhoon intensity before making landfall, then dissipated over the rugged terrain of southeastern China. The final warning was issued at 020600Z.

III. FORECAST PERFORMANCE

Because the passage of two tropical cyclones to the east eroded the subtropical ridge, the steering flow in which Nat was embedded was weak. Track forecasting proved to be a real challenge, but forecast errors were respectable considering the erratic nature of the tropical cyclone. From the suite of objective aids, FBAM and CSUM seemed to provide the best overall performance. They both simulated the loop to the south caused by the surge into Tropical Storm Luke (20W); however, they were less successful in forecasting the binary interaction with Super Typhoon Mireille (21W). OTCM and NOGAPS had a very difficult time with this system. As an example, Figure 3-22-4 shows the forecast guidance for the 230000Z warning while Nat was over southern Taiwan.

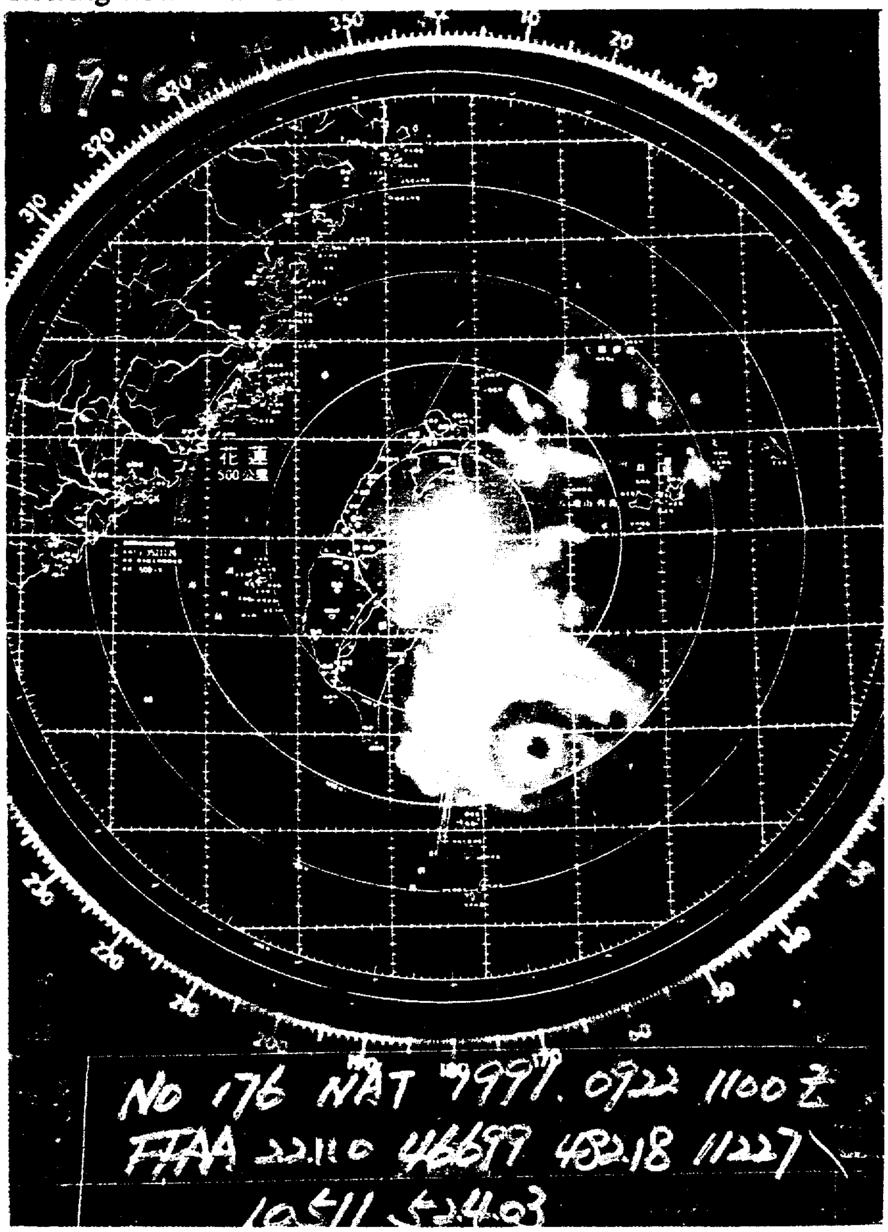


Figure 3-22-2. The radar at Haulien (WMO 46699), Taiwan paints Nat's concentric rainbands (221300Z September photo courtesy of the Central Weather Bureau, Taipei, Taiwan).

IV. IMPACT

Even though Nat was small in size and no reports were received, the typhoon's crossing of extreme southern Taiwan and, later, the southern coast of China must have disrupted communications and transportation and caused some localized damage.

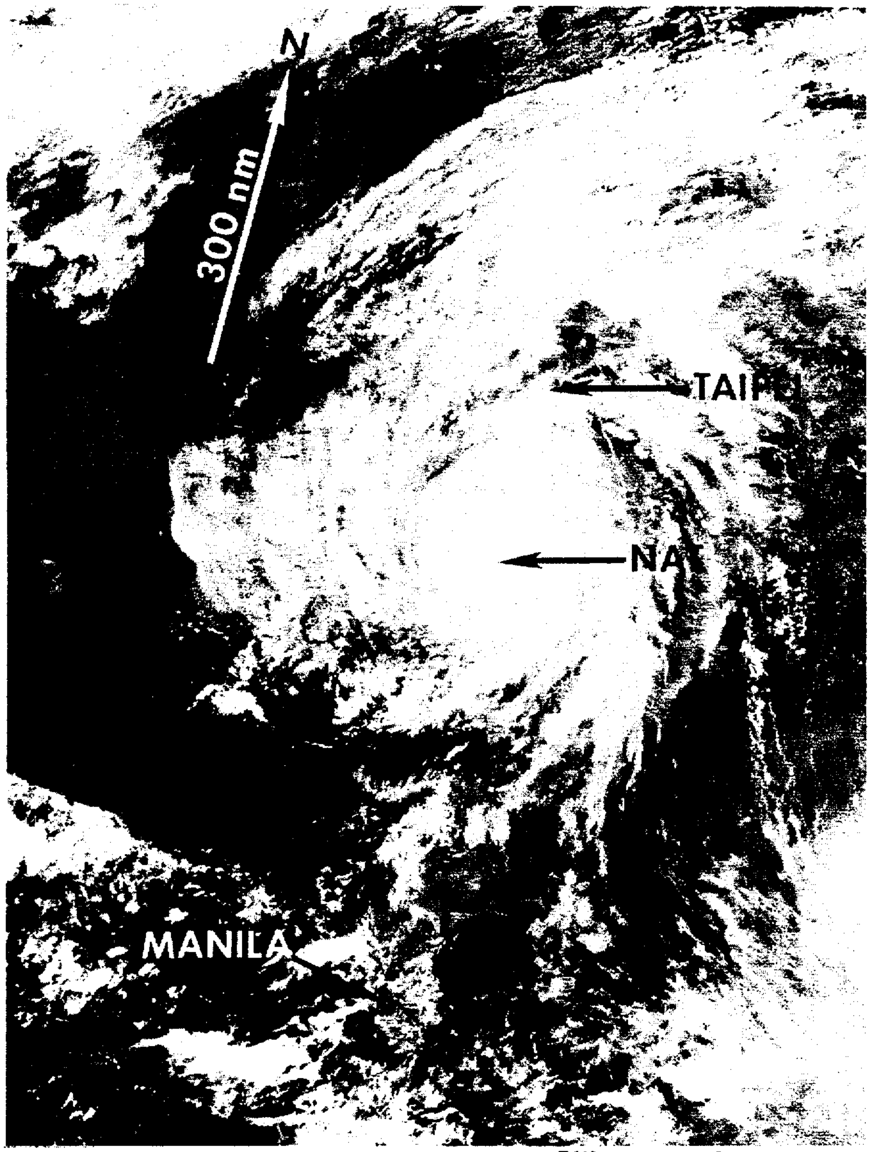


Figure 3-22-3. Nat crosses southern Taiwan (230110Z September DMSP visual imagery).

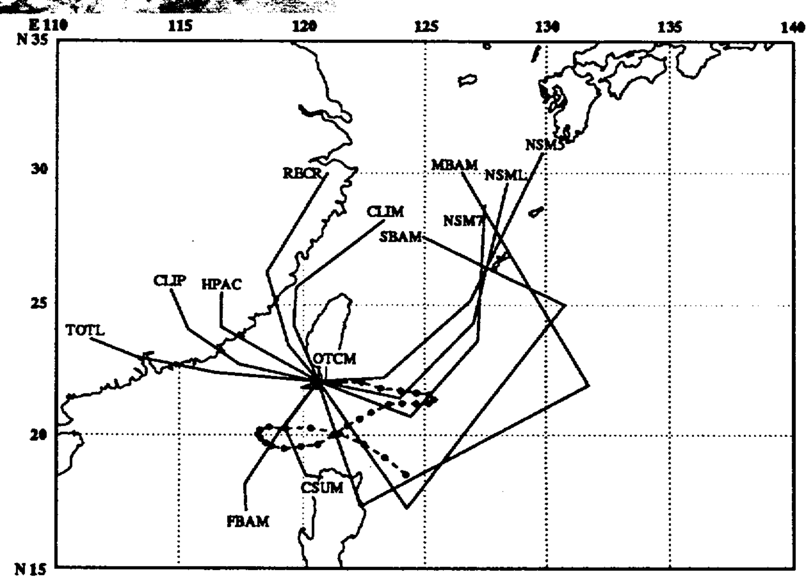
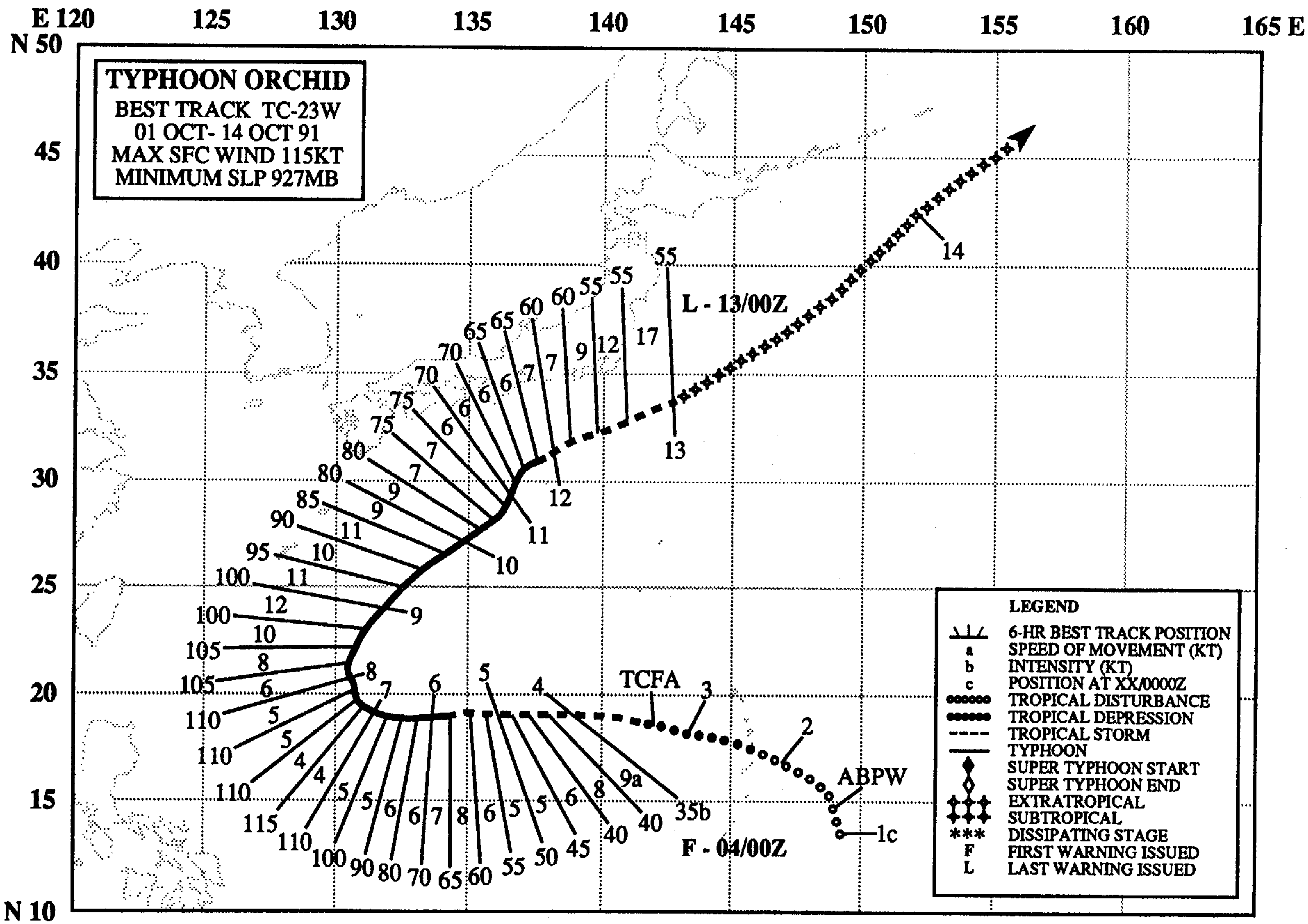


Figure 3-22-4. Forecast guidance supporting the 230000Z September warning for Typhoon Nat.


TYPHOON ORCHID
BEST TRACK TC-23W
01 OCT- 14 OCT 91
MAX SFC WIND 115KT
MINIMUM SLP 927MB
L - 13/00Z
F - 04/00Z
TCFA
ABPW
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TYPHOON ORCHID (23W)

I. HIGHLIGHTS

Typhoon Orchid (23W) was the first tropical cyclone to develop during the month of October. Orchid's formation coincided with Typhoon Pat's (24W) and, as they matured, they interacted, causing Orchid to slow to 6 kt (11 km/hr) about 200 nm (370 km) off the coast of Japan. This brought prolonged rains and widespread flooding to Tokyo and surrounding cities.

II. TRACK ANDINTENSITY

Orchid formed northwest of Guam in a broad monsoon trough that extended from the South China Sea eastward through the Caroline Islands and was included as a suspect area on the 010600Z October Significant Tropical Weather Advisory. A mid-latitude trough weakened the mid-tropospheric subtropical ridge to allow the tropical disturbance to slowly gain latitude. When low-level convergence created by a surge in the monsoon westerlies enhanced convection, forecasters issued a Tropical Cyclone Formation Alert at 030800Z. The first warning followed on Tropical Depression 23W at 040000Z. (Post analysis of satellite derived current intensity estimates indicated tropical storm intensity most probably had been reached 12 hours before the first warning through normal, rather than rapid deepening.) Orchid tracked due westward south of the re-established subtropical ridge and developed into a typhoon. Orchid's intensity peaked at 120 kt (62 m/sec) just before recurvature, as increased low-level convergence in the southern quadrant enhanced convection, and dual outflow channels aloft were present. Recurvature occurred near 130°E as the mid-tropospheric subtropical ridge receded eastward, allowing Orchid to move north and recurve. Typhoon Orchid slowly accelerated after recurvature, but on 10 October it slowed down south of Japan as interaction started with Typhoon Pat (24W) (Figure 3-23-1). Over a 40-hour period from approximately 100600Z - 120000Z, Orchid "stair-stepped" to the north then back to the northeast apparently due to some binary interaction with Typhoon Pat. As Pat recurved to the east of Orchid and accelerated, Orchid started speeding up, following Pat into the westerlies, and slowly weakening. The final warning was issued at 130000Z as Orchid transitioned into an extratropical low pressure system.

III. FORECAST PERFORMANCE

During recurvature, Orchid was expected to make a more gradual, broader turn around the ridge because the steering flow was weak, as evidenced by the slow speed of motion from 4 to 6 kt (7 to 11 km/hr) on 6 to 7 October. Initially, the typhoon was forecast to pass near Okinawa, west of the guidance provided by most of the dynamic aids (Figure 3-23-2). After recurvature, cross-track forecasts were excellent, although the along-track speed errors were large because the expected forecast acceleration did not take place until Pat moved north of Orchid.

VI. IMPACT

Typhoon Orchid spent much of its life over the open ocean, away from land. However, its slow movement south of Japan caused prolonged rains there, and created huge ocean swells, which combined with those from Pat to produce high waves and hazardous surf as far away as Guam on October 12, where the surf claimed 2 lives. On 14 October, landslides, floods, heavy winds, and torrential rains were reported in Tokyo and the surrounding cities. One person died after being swept away by a swollen river, 14 people were injured and wind gusts to 50 kt (26 m/sec) were recorded in and around Tokyo. Orchid interrupted transportation across the island, produced 96 landslides, flooded over 675 homes, and caused extensive road damage in Japan.

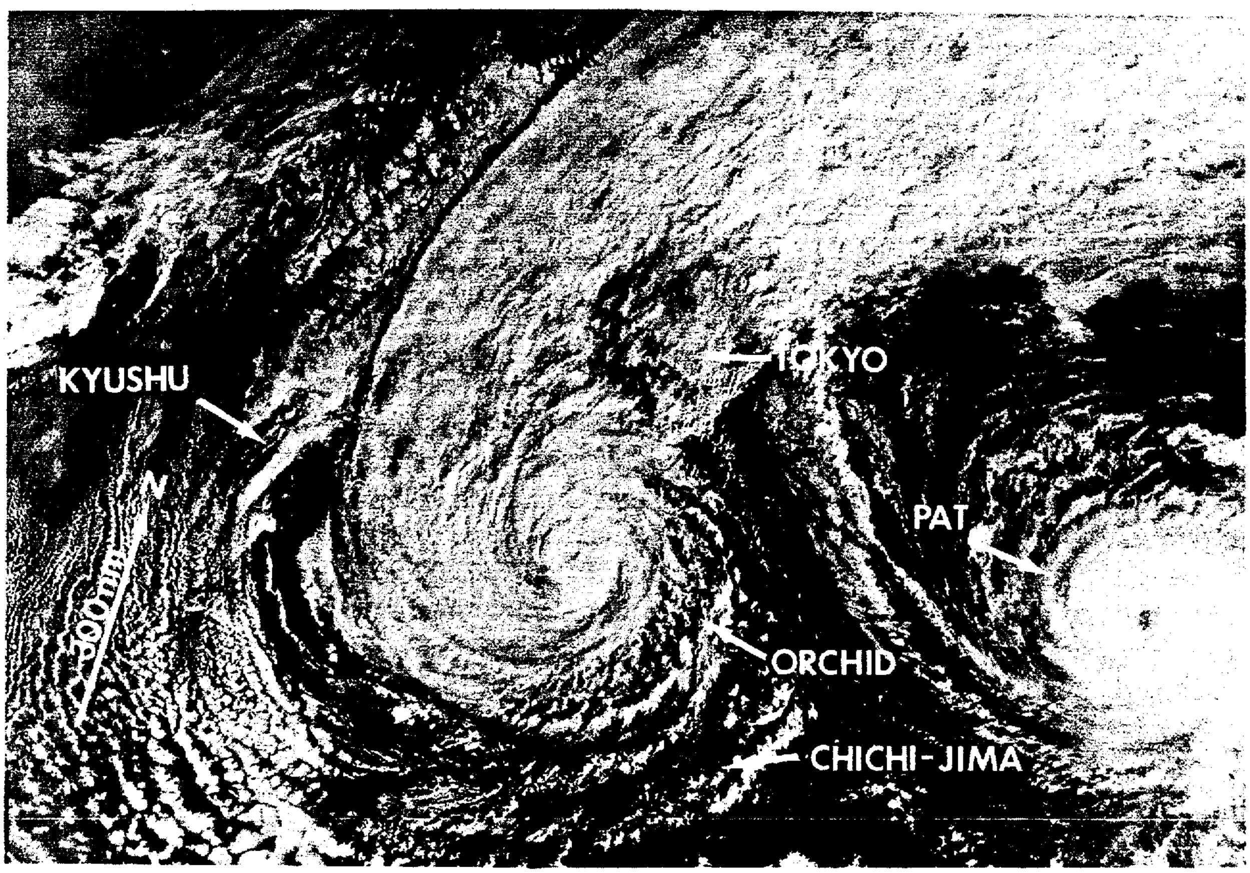


Figure 3-23-1. Typhoon Orchid slowly weakens as it parallels the south coast of Honshu, Japan (112322Z October DMSP visual imagery).

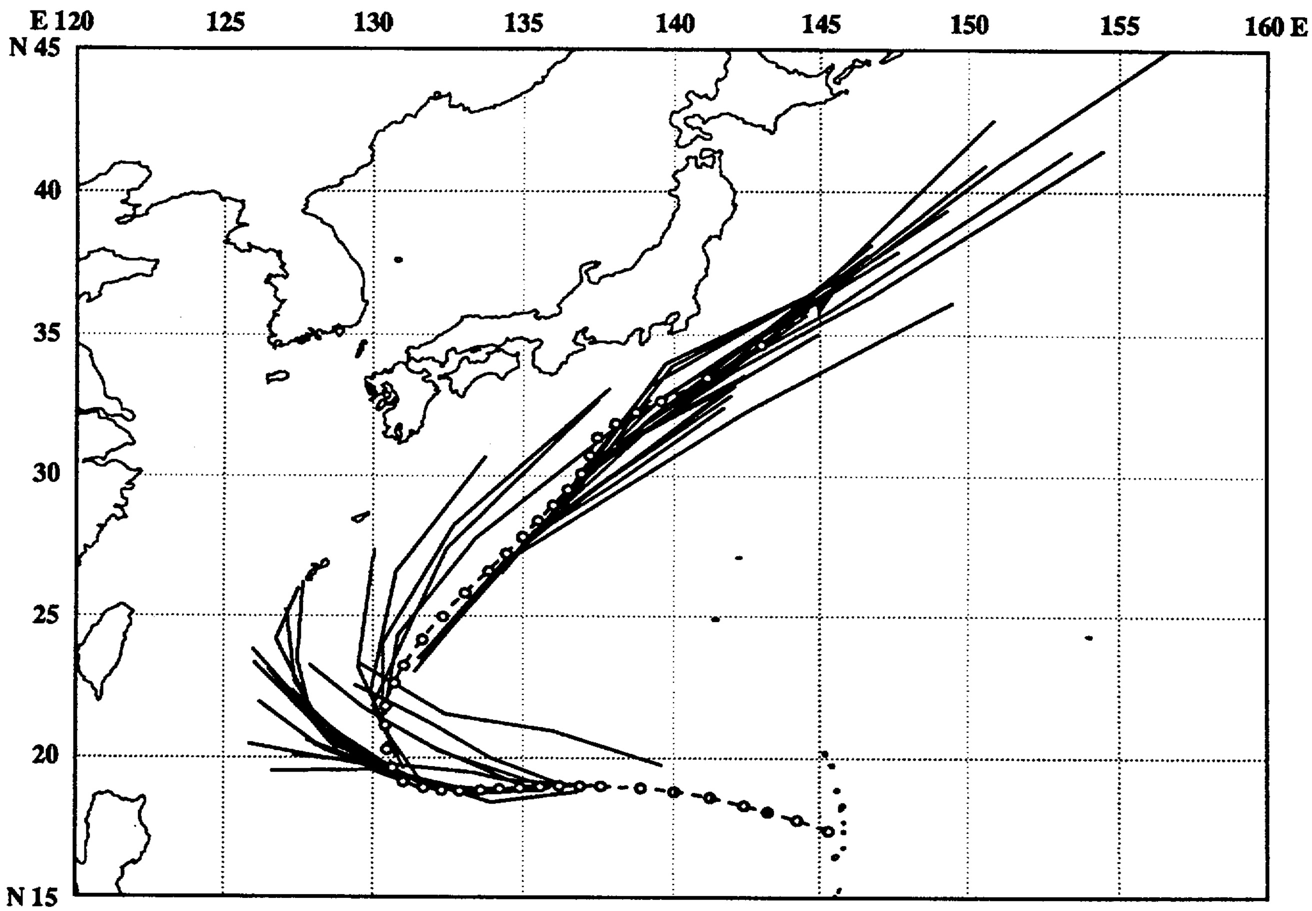
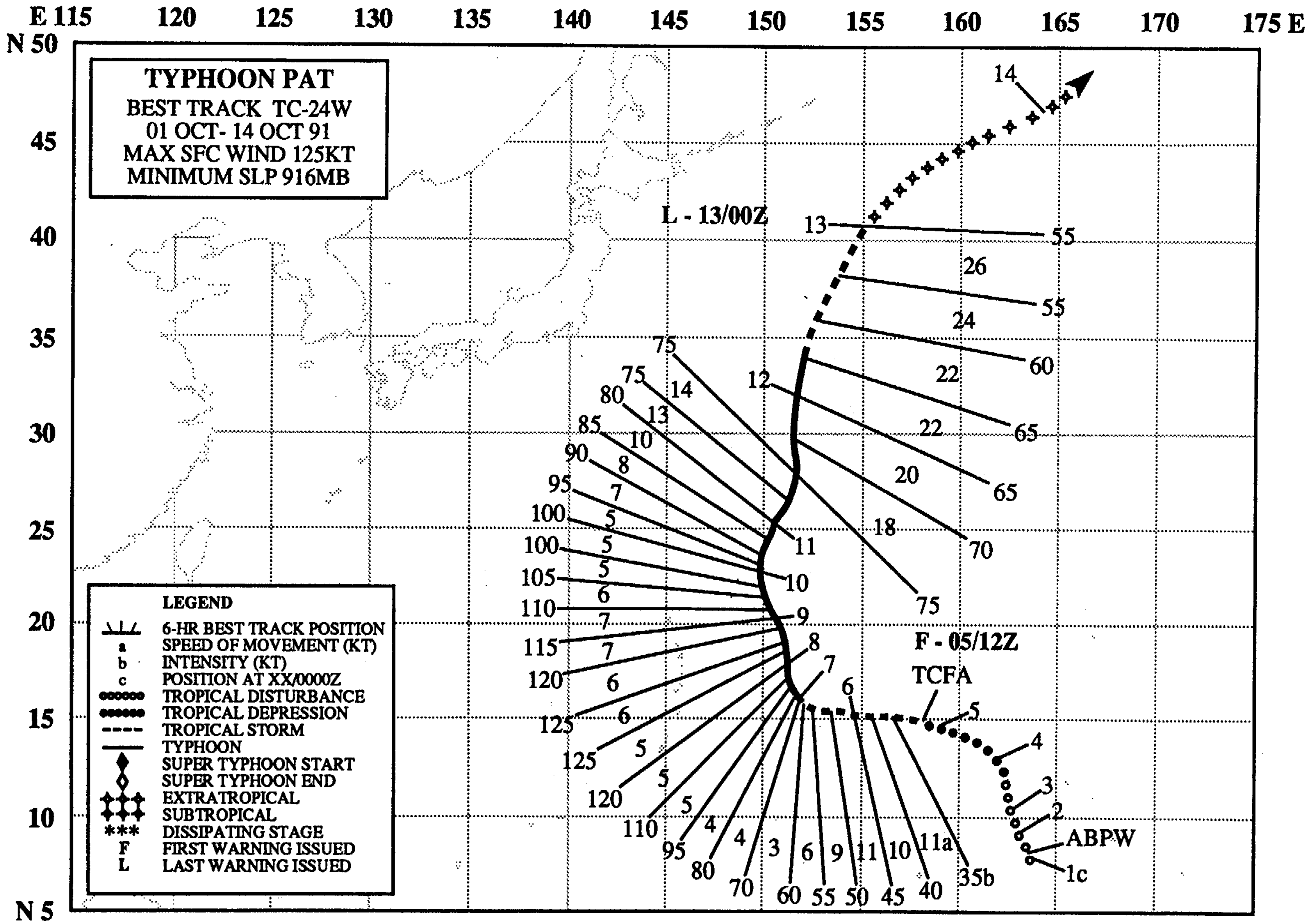


Figure 3-23-2. JTWC forecasts when compared to the final best track show that Orchid turned north sooner than expected.


TYPHOON PAT
BEST TRACK TC-24W
01 OCT- 14 OCT 91
MAX SFC WIND 125KT
MINIMUM SLP 916MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
L - 13/00Z
F - 05/12Z
TCFA
ABPW
E 115
120
125
130
135
140
145
150
155
160
165
170
175 E
N 50
45
40
35
30
25
20
15
10
N 5

TYPHOON PAT (24W)

I. HIGHLIGHTS

Typhoon Pat developed at the same time in early October as Typhoon Orchid (23W). Its rapid intensification phase was correctly predicted by a recently developed pixel-counting forecast scheme. Although Pat initially trailed Orchid as the two tropical cyclones matured, it accelerated and was the first to become extratropical.

II. TRACK AND INTENSITY

After Typhoon Nat (22W) dissipated over southeastern China and the monsoon trough re-established itself eastward into the Caroline and Marshall Islands, two tropical disturbances formed in this trough. These disturbances were discussed on the 010600Z October Significant Tropical Weather Advisory. Pat developed from the disturbance in the western Marshall Islands, and the other disturbance to the west became Typhoon Orchid (23W). Initially, tropical cyclone development was hampered by vertical wind shear. On 4 October, vertical shear decreased and the depression began to slowly intensify. Based on a steady increase in convective organization, a Tropical Cyclone Formation Alert was issued at 050630Z, followed by the first warning at 051200Z. Pat intensified at a normal rate of 20 kt (10 m/sec) per day until 061800Z, when it began to rapidly intensify (Figure 3-24-1). At about the same time, the ridge weakened to the north, allowing the typhoon's track to change from west-northwestward to north-northwestward for the next 72 hours. Typhoon Pat attained a maximum

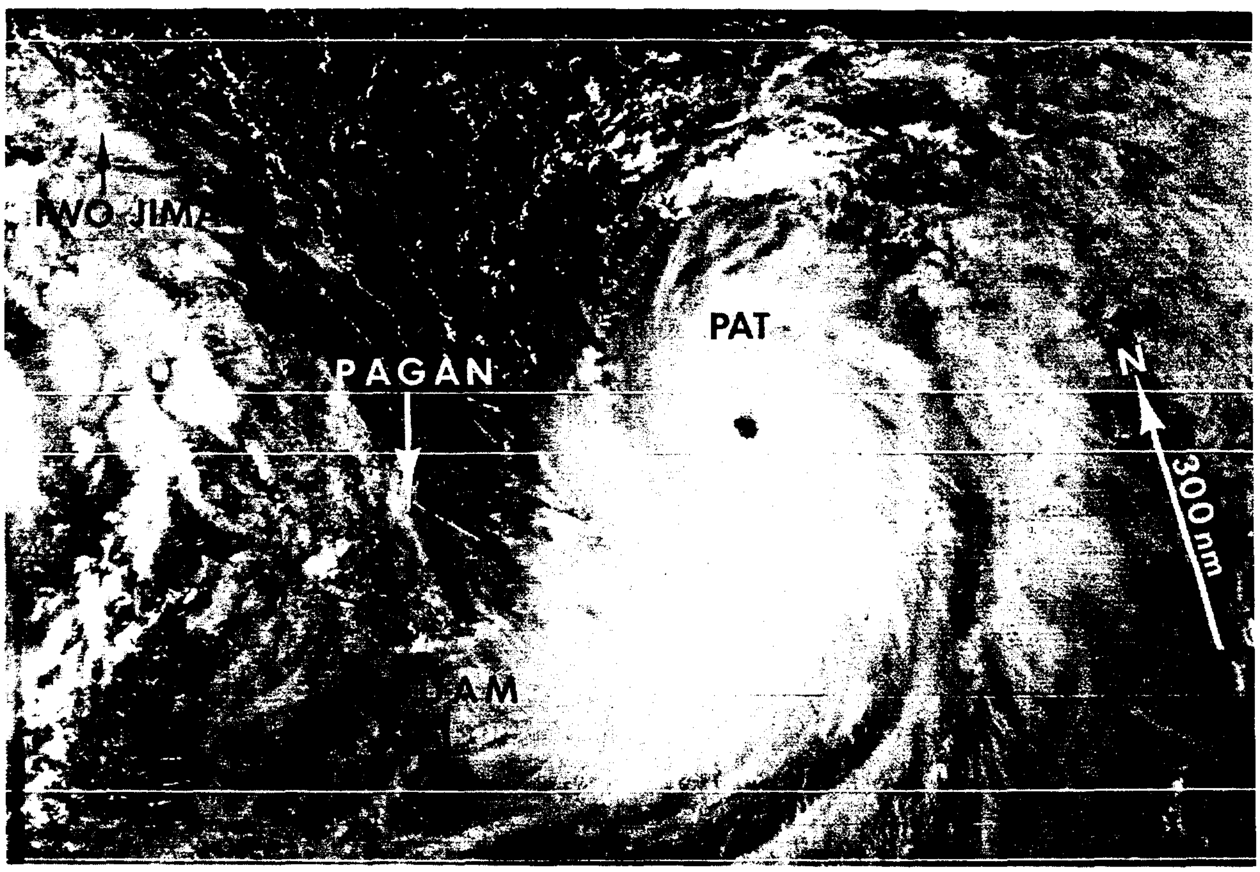


Figure 3-24-1. Typhoon Pat nears it maximum intensity (072237Z October DMSP visual satellite imagery).

intensity of 125 kt (64 m/sec) on 8 October, approximately 320 nm (590 km) east of Pagan Island in the northern Mariana Islands. As the system began to weaken, the subtropical high located to the east maintained its strength and position. As a result, Pat began to approach Orchid, which was recurving south of Japan. By 100000Z, the two systems had closed to within 1000 nm (1850 km) of each other. Instead of undergoing binary interaction and orbiting around a common midpoint, Pat and Orchid maintained their separation and moved in tandem to the north-northeast (Figure 3-24-2). Although initially the trailing cyclone, Pat accelerated poleward first, and the slow-moving Orchid followed in its wake. Both became extratropical at 130000Z.

III. FORECAST PERFORMANCE

Interaction with Orchid was the most difficult portion of Pat's track to forecast. Initially the prognostic messages indicated that Orchid, which had recurved first and was located further north than Pat, was more likely to be the first to accelerate northeastward. However, Pat became the first to accelerate. Surprisingly, climatology was the best-performing forecast aid at 72 hours, with a forecast error of only 201 nm (370 km).

The start of Pat's rapid intensification on 7 October was successfully predicted by a new pixel-counting technique (Mundell, 1990) which compares the ratio of inner-radius convection to outer-radius convection to forecast rapid intensity change (Figure 3-24-3). Overall intensity forecasting errors were slightly higher than the average.

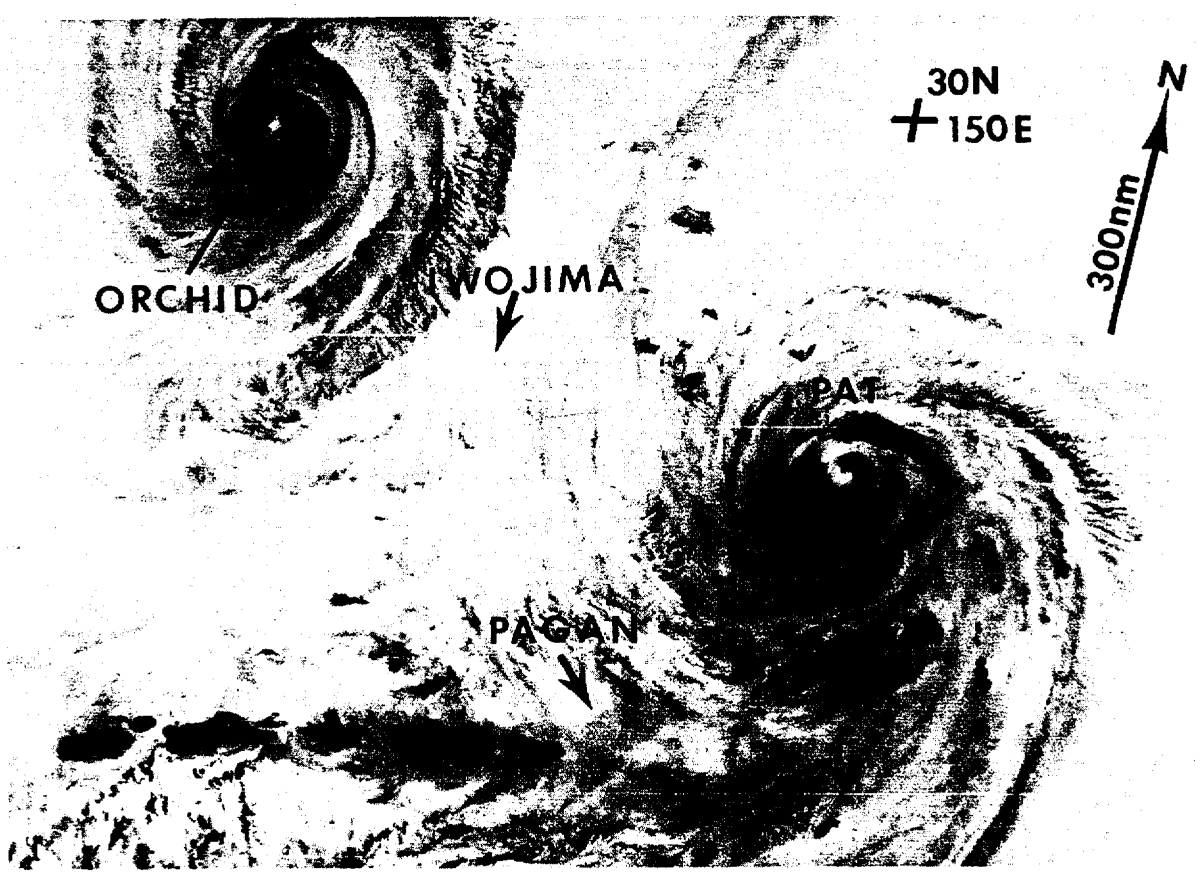


Figure 3-24-2. Typhoons Pat and Orchid (23W) are both moving north-northeastward in tandem (101011Z October DMSP infrared imagery).

IV. IMPACT

JTWC did not receive any information of direct impacts of Pat. However, indirectly, the slow movement of Pat and Orchid set up significant long period ocean swells that gave Guam some of its largest surf of the year. At least two people lost their lives on Guam due to the high surf.

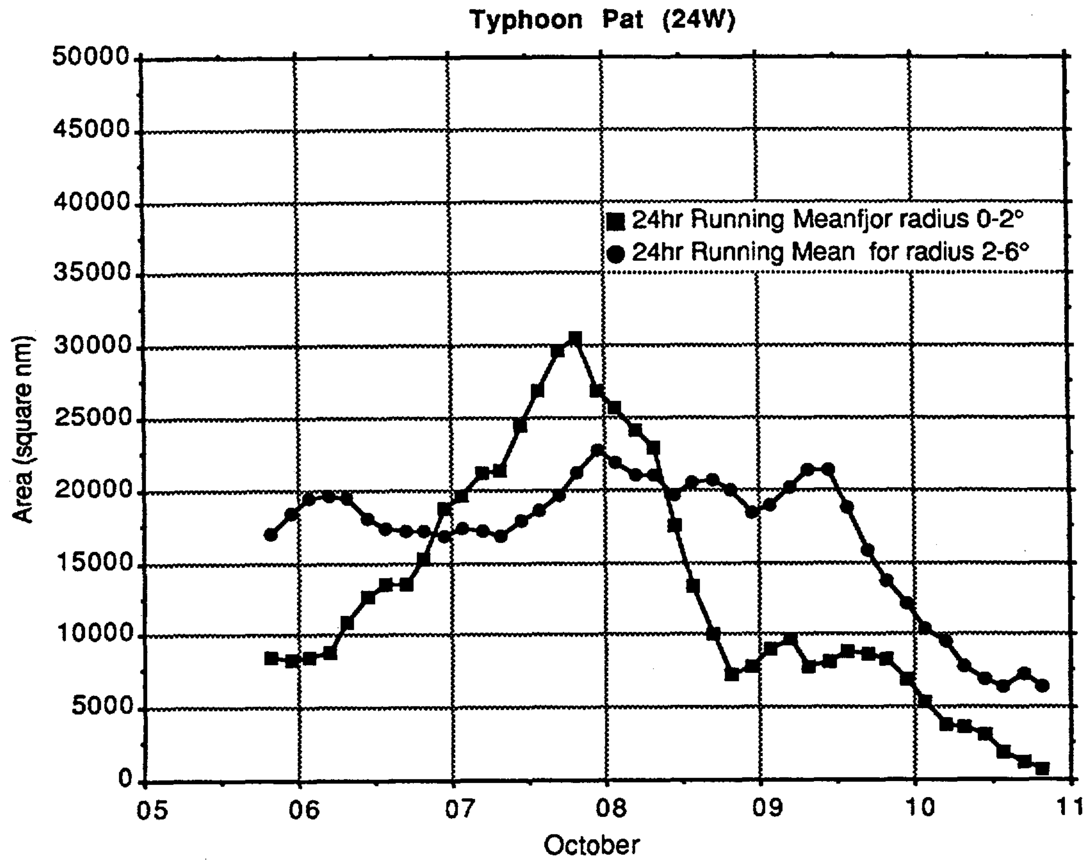
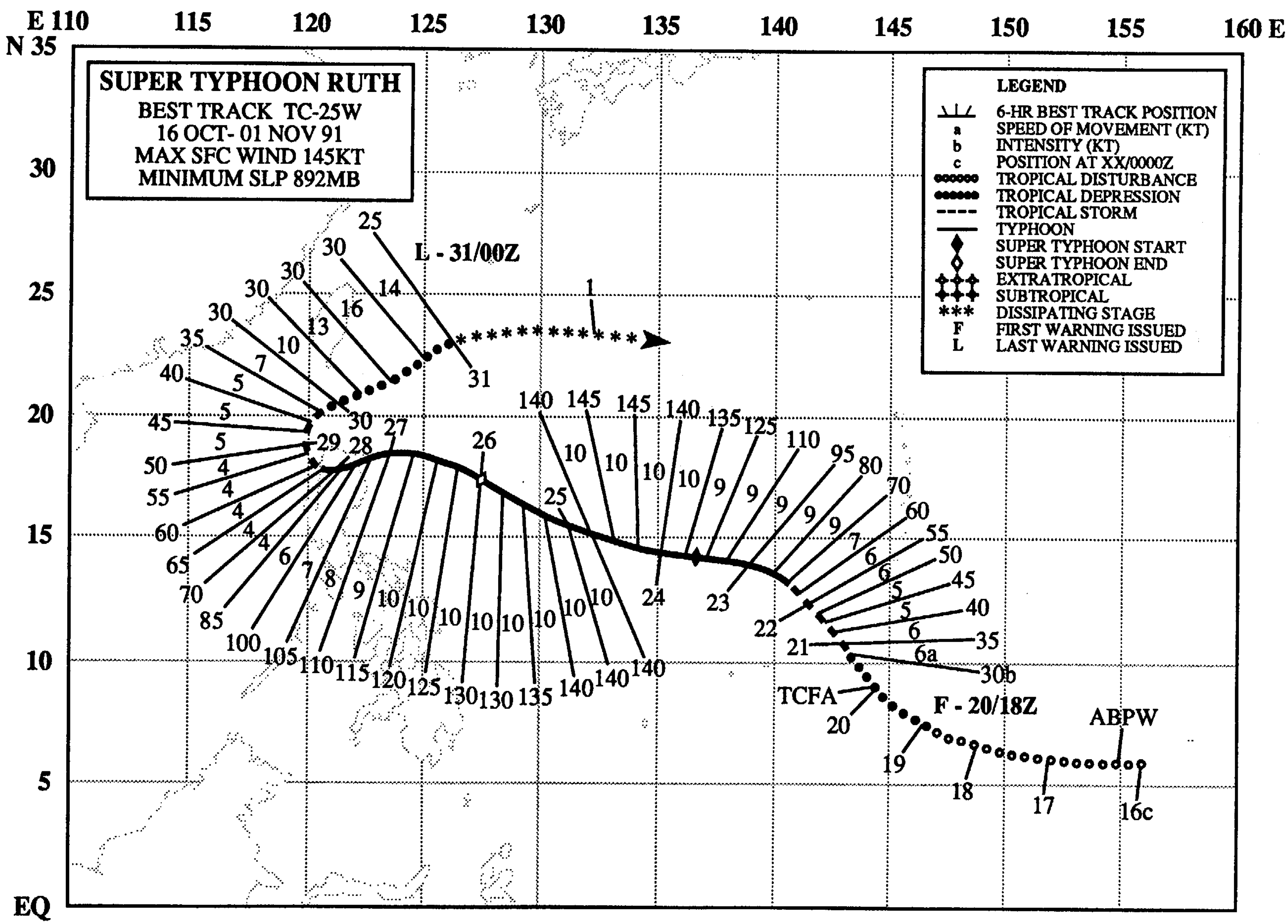


Figure 3-24-3. Time series of the relative amounts of inner convection (measured within 2° of the cloud system center) colder than -75°Celsius and outer convection (measured within 2°-6° of the center) colder than -65°Celsius. According to Mundell (1990), when the lines representing 24-hour running mean averages of both inner and outer convection cross, rapid intensification is likely to occur over the next 12 hours.



SUPER TYPHOON RUTH
BEST TRACK TC-25W
16 OCT- 01 NOV 91
MAX SFC WIND 145KT
MINIMUM SLP 892MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 110
115
120
125
130
135
140
145
150
155
160 E
N 35
30
25
20
15
10
5
EQ
L - 31/00Z
F - 20/18Z
TCFA
ABPW
16c
30b
6a

SUPER TYPHOON RUTH (25W)

I. HIGHLIGHTS

Super Typhoon Ruth was the second most intense tropical cyclone of 1991. With regard to intensity, forecasters successfully used climatological analogs to anticipate Ruth's rapid deepening to super typhoon intensity in the Philippine Sea. However, in contrast, the track forecasts based on NOGAPS prediction of early recurvature had the largest forecast track errors of the year.

II. TRACK AND INTENSITY

Ruth appeared as a tropical disturbance with a closed circulation at the surface between Chuuk and Pohnpei. Observed pressure falls of 1 to 2 mb over the previous 24 hours persuaded forecasters to mention the disturbance on the 160600Z October Significant Tropical Weather Advisory as an area with fair potential for development. On 18 and 19 October, there was a steady increase in convection as the disturbance moved west-northwestward through the Caroline Islands. The increased convection prompted the issuance of a Tropical Cyclone Formation Alert at 200100Z. Based on a Dvorak intensity estimate of 25 kt (13 m/sec) and increased convective organization, the first warning on Tropical Depression 25W was issued at 201800Z.

Figure 3-25-1. Ruth at super typhoon intensity in the Philippine Sea (231816Z October NOAA infrared imagery).

Ruth intensified steadily as it moved northwestward between Guam and Ulithi. On 22 October, an eye formed as the tropical cyclone "stair stepped" westward. After assuming a west-northwestward track across the Philippine Sea, Ruth rapidly intensified, reaching super typhoon intensity only 30 hours after its eye first appeared on satellite imagery (Figure 3-25-1). Ruth's track and explosive intensity increase were consistent with climatological guidance. Nine analog tropical cyclones from a 20-year data set (Table 3-25-1) were found. Six of the nine had rapidly intensified to super typhoon intensity, and the majority had maintained a west-northwest track across the Philippine Sea. Ruth's intensity peaked at 145 kt (75 m/sec) at 240600Z and then slowly weakened as the typhoon approached northern Luzon. During this weakening phase, the eye expanded from a diameter of 10 nm (19 km) to 60 nm (110 km).

On 25 October, a mid-tropospheric trough moving eastward from China temporarily weakened the ridge and Ruth turned northwestward. Then the subtropical ridge re-established itself, and on 27 October Ruth tracked west-southwestward into northern Luzon. The typhoon lashed the northern coast of Luzon with winds in excess of 100 kt (51 m/sec) before weakening to tropical storm intensity over land. On 28 October another migrating mid-tropospheric trough, deeper than the previous one, picked up Tropical Storm Ruth and caused it to recurve south of Taiwan. The tropical cyclone continued to weaken as it moved northeastward, and JTWC issued the final warning on the system at 310000Z.

III. FORECAST PERFORMANCE

The track forecasts were excellent until 250000Z, when the forecast scenario changed from straight-running, west-northwestward to recurvature (Figure 3-25-2). Low track and intensity errors for the first 17 warnings had been a reflection of the climatological analogs.

Starting with the 231200Z dynamic model run, the NOGAPS prognoses began to deviate from the climatological track guidance by predicting early recurvature and then acceleration (Figure 3-25-3). Based on NOGAPS' previous successes, the forecast scenario switched from straight runner to recurver for the 250000Z through 261200Z warnings. When Ruth continued to move west-northwestward and the upper air analyses indicated 500 mb heights were rising over Taiwan, it became apparent that the NOGAPS guidance was erroneous. The result was six 72-hour forecast with errors in excess of 500 nm (925 km), including two over 900 nm (1665 km) - the largest busts of the year.

IV. IMPACT

Super Typhoon Ruth was the most intense tropical cyclone of 1991 to strike Luzon. On northern Luzon 12 people were killed as Ruth triggered numerous landslides and flooding leaving at least 76,000 residents homeless. Fortunately, very little rain fell near Mount Pinatubo where it would have caused mudflows, lahars, and additional devastation. At sea, 18 lost their lives when the freighter **Tung Lung** sank west of Taiwan. Another 18 crewman were rescued from heavy seas after the freighter

Table 3-25-1. Listing of nine analog tropical cyclones from 1970 to 1990 which had the greatest similarity to Ruth's track and intensity, along with their 24-, 48-, and 72-hour track and intensity change.

TC	DTG	INITIAL PSN (INT)	24 HOUR MOVMT (INT)	48 HOUR MOVMT (INT)	72 HOUR MOVMT (INT)
Ruth	91102118	12.0N 142.0E (50)	NW at 7 kt (80)	W at 9 kt (135)	WNW at 10 kt (140)
Irma	71111106	11.2N 139.4E (60)	NW at 15 kt (95)	NW at 15 kt (150)	NW at 9 kt (120)
Patsy	73100706	13.4N 140.8E (45)	WNW at 7 kt (65)	WNW at 9 kt (95)	WNW at 10 kt (140)
Louise	76103112	11.0N 142.1E (50)	W at 12 kt (75)	WNW at 14 kt (135)	WNW at 13 kt (140)
Kim	77110800	13.2N 147.4E (50)	W at 15 kt (95)	W at 14 kt (120)	W at 10 kt (120)
Tip	79100906	12.7N 145.8E (55)	W at 10 kt (85)	WNW at 6 kt (140)	NW at 7 kt (165)
Betty	80103006	11.7N 149.1E (55)	WNW at 20 kt (80)	W at 16 kt (95)	W at 11 kt (100)
Marge	83110118	13.6N 141.1E (45)	WNW at 8 kt (75)	WNW at 8 kt (130)	WNW at 7 kt (140)
Dot	85101400	11.6N 142.4E (50)	W at 12 kt (75)	WNW at 10 kt (140)	W at 13 kt (150)

Southern Cross sank northeast of Taiwan.

The large track forecast errors resulted in a short notice for DOD assets on northern Luzon to prepare for the typhoon and unnecessary typhoon preparations from Okinawa to Japan.

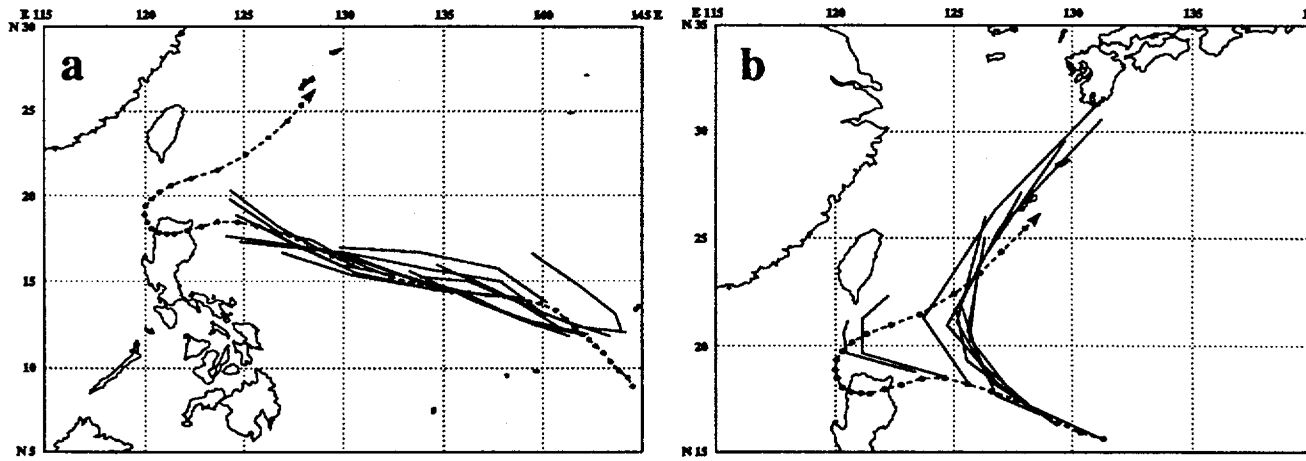


Figure 3-25-2. (a) Comparison of the first 17 warnings (201800Z to 241800Z) to the official JTWC best track and, (b) comparison of the next nine warnings (250000Z to 270000Z) to the official JTWC best track.

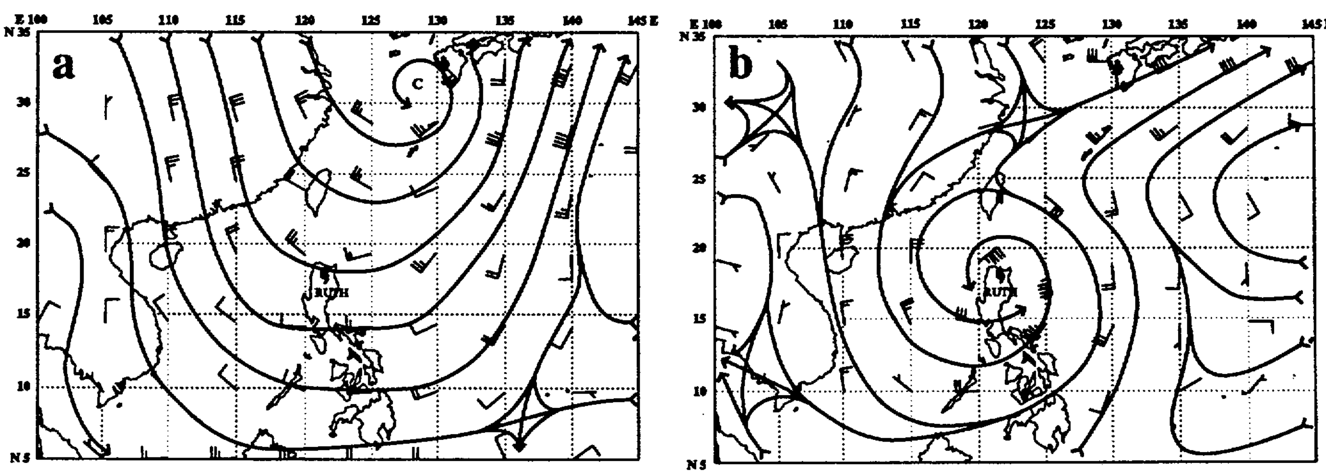
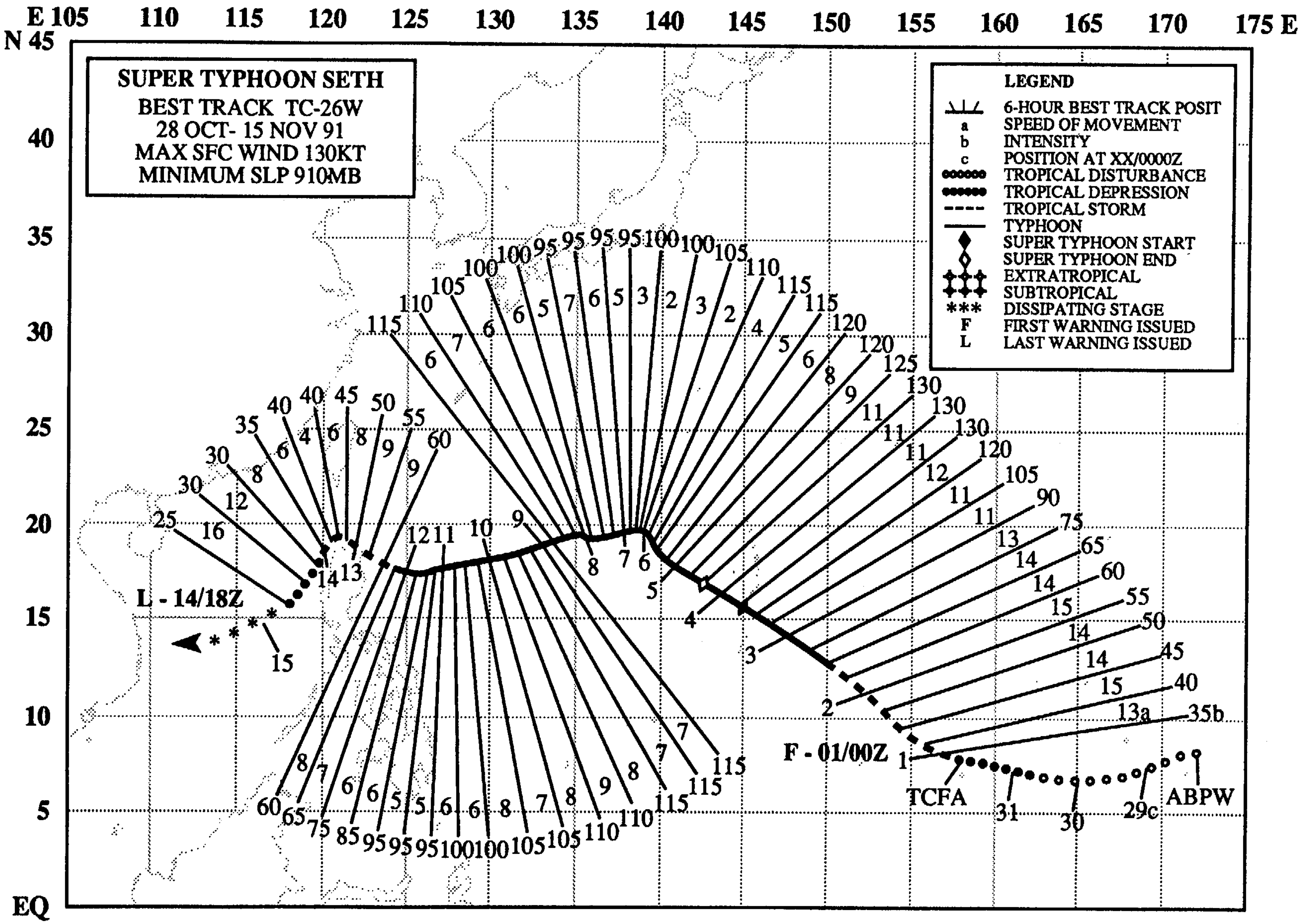


Figure 3-25-3. (a) Comparison of the NOGAPS 250000Z 700-mb 72-hour forecast, valid at 280000Z, to the (b) verifying NOGAPS analysis at 280000Z.


SUPER TYPHOON SETH
BEST TRACK TC-26W
28 OCT- 15 NOV 91
MAX SFC WIND 130KT
MINIMUM SLP 910MB
LEGEND
6-HOUR BEST TRACK POSIT
a SPEED OF MOVEMENT
b INTENSITY
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
L - 14/18Z
F - 01/00Z
TCFA
ABPW
E 105
110
115
120
125
130
135
140
145
150
155
160
165
170
175 E
N 45
40
35
30
25
20
15
10
5
EQ

SUPER TYPHOON SETH (26W)

I. HIGHLIGHTS

Super Typhoon Seth was the first of six tropical cyclones to reach at least typhoon intensity in the month of November. This was the most active November in the western North Pacific since 1964. Forecasts for Seth's generally westward track were complicated by the normally reliable objective guidance suggesting recurvature which did not occur.

II. TRACK AND INTENSITY

Seth originated as a weak disturbance in the southern Marshall Islands, and was mentioned on the 280600Z October Significant Tropical Weather Advisory. Synoptic and satellite data for the next several days indicated slow development. A Tropical Cyclone Formation Alert was issued at 311730Z October based on a significant increase in the amount and organization of convection over the preceding 12 hours. More convection and the detection of a circulation defined by low-level cloud lines on visual satellite imagery prompted the first warning at 010000Z November.

The tropical cyclone continued tracking west-northwestward and intensified rapidly. With a faster than normal rate of intensification supported by dual outflow channels aloft, the system quickly peaked, reaching a maximum intensity of 130 kt (67 m/sec) at 031800Z (Figure 3-26-1). On 4 November Seth started to slow as it approached the axis of the subtropical ridge and the anticipated point of recurvature. However, the ridge strengthened as the super typhoon weakened, and Seth became almost stationary for 24 hours before resuming a slow, west-southwestward track on 6 November.

For the next 5 days, Seth continued west-southwestward and briefly reintensified. During this period Seth and Tropical Storm Verne (28W), located to the east, closed to within 800 nm (1480 km) of each other. While the influence was nominal due to the large separation distance, Verne weakened the ridge to the north and contributed to the slowing of Seth. On 12 November Seth gradually turned northwestward as it approached northern Luzon. This turn appeared to be in response to a weakness in the ridge west of Taiwan. However, once again the ridge strengthened, and the tropical cyclone turned southwestward along the edge of a low-level surge from the northeast. Due to shear and land affects, Seth continued to weaken as it moved into the South China Sea and dissipated. The final warning was issued at 141800Z.

III. FORECAST PERFORMANCE

Seth's track was difficult to forecast because of the narrow subtropical ridge and the objective guidance which kept suggesting recurvature. As the track neared 140°E longitude, the Colorado State University Model (CSUM) proved to be the best performer, aided by its tendency to be slow in recurvature situations. Once Seth moved westward from the bifurcation point near 140°E, JTWC's forecast performance improved significantly (Figure 3-26-2).

IV. IMPACT

As Seth brushed by Saipan in the Northern Mariana Islands on 3 November no fatalities were reported, but significant property and crop damage occurred. Estimates of damage to public facilities alone were as high as US$2 million. Families were evacuated from low lying areas, and 9.5 inches (240 mm) of rain caused widespread flooding. Later, when Seth tracked through the Luzon Strait, no reports of property damage or injury were received.

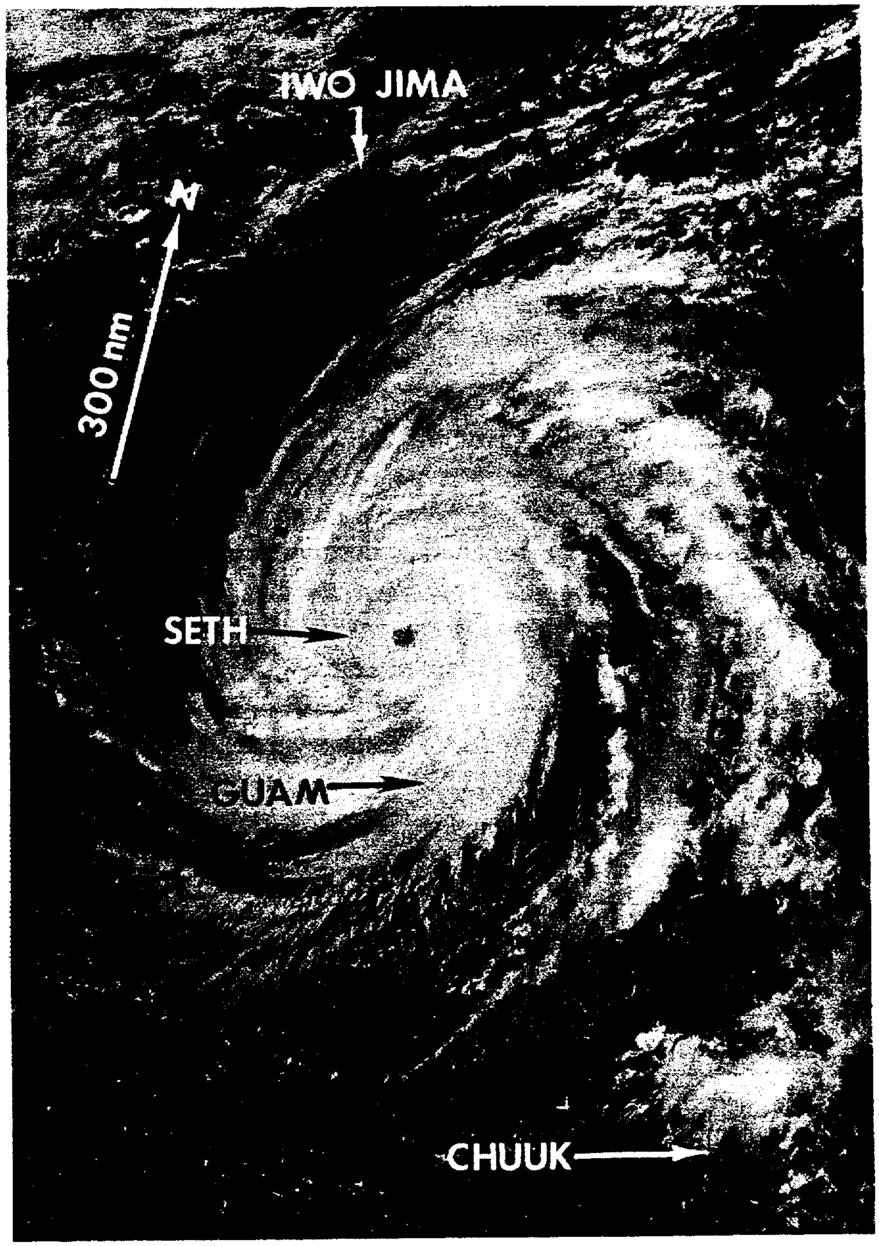


Figure 3-26-1. Satellite imagery shows Super Typhoon Seth at its peak intensity (032330Z November DMSP visual imagery).

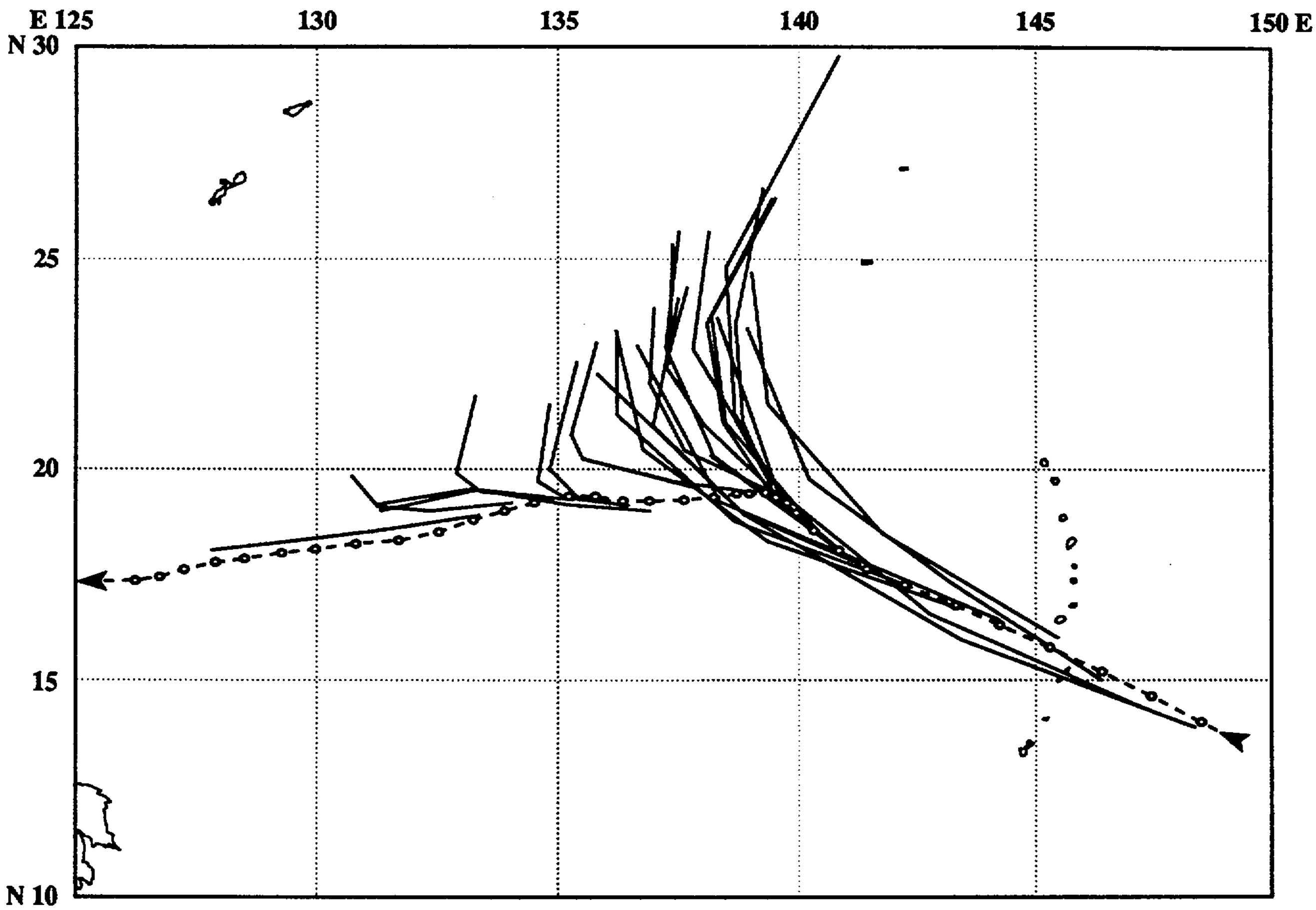
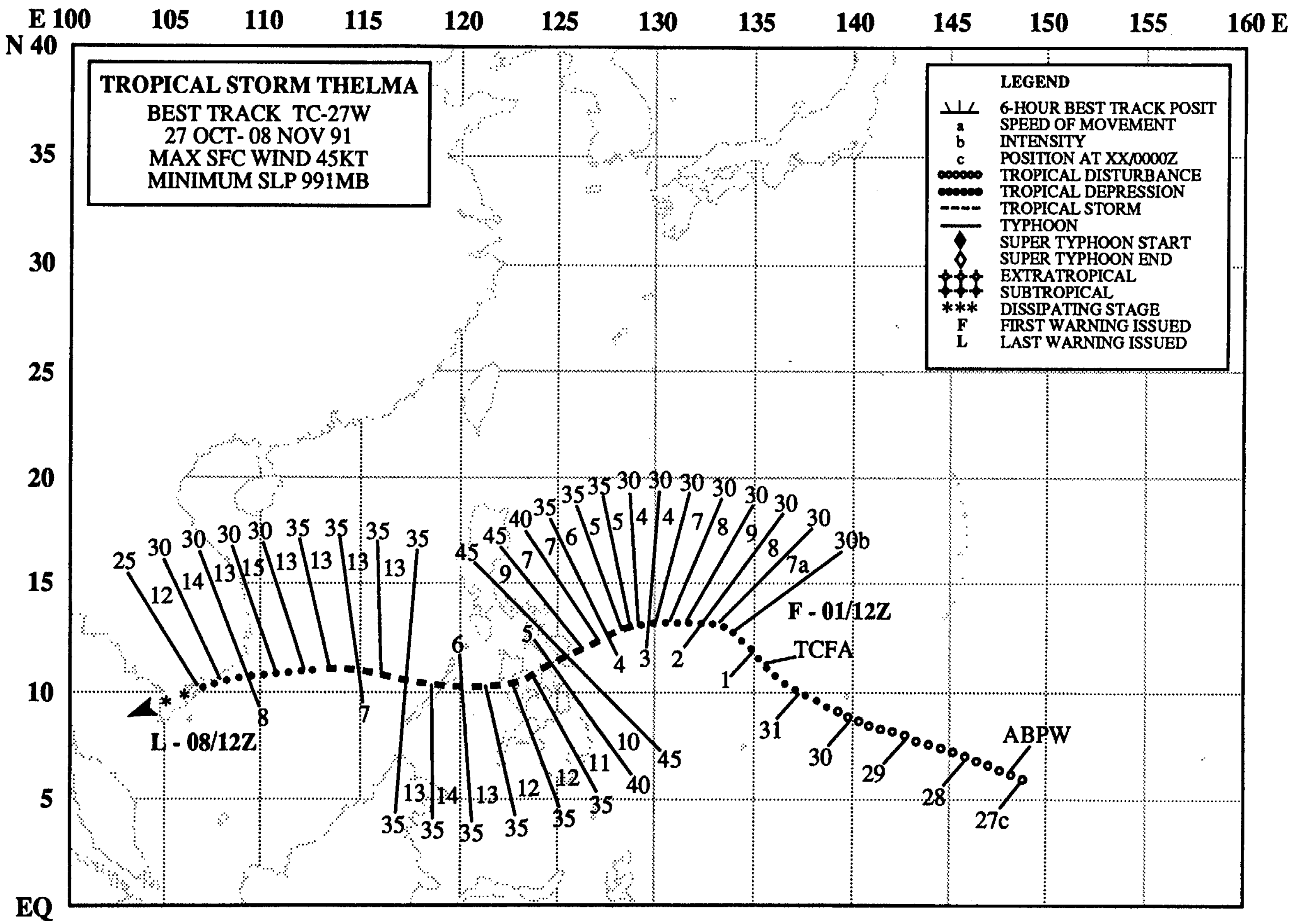


Figure 3-26-2. JTWC forecasts, when compared to the final best track, show gradual improvement after the bifurcation point near 140°E.



TROPICAL STORM THELMA
BEST TRACK TC-27W
27 OCT- 08 NOV 91
MAX SFC WIND 45KT
MINIMUM SLP 991MB
LEGEND
6-HOUR BEST TRACK POSIT
a SPEED OF MOVEMENT
b INTENSITY
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
F - 01/12Z
TCFA
ABPW
L - 08/12Z
E 100
105
110
115
120
125
130
135
140
145
150
155
160 E
N 40
35
30
25
20
15
10
5
EQ

TYPHOON THELMA (27W)

I. HIGHLIGHTS

The worst loss of life due to a natural disaster in the western North Pacific during 1991 occurred when Tropical Storm Thelma made landfall in the Visayan Islands of the Philippines. News accounts estimated that 6000 people died and 20,000 people were left homeless by catastrophic events resulting from the passage of the tropical storm including the failure of a dam, landslides and extensive flash flooding. The highest casualties occurred at Ormoc on Leyte Island where widespread logging in recent years had stripped the hills above the port city bare of vegetation.

II. TRACK AND INTENSITY

Thelma began as a tropical disturbance in the eastern Caroline Islands, and was first mentioned on the 270600Z October Significant Tropical Weather Advisory. After persisting for 4 days, its convection rapidly increased, the system center reorganized, and JTWC forecasters issued a Tropical Cyclone Formation Alert at 311900Z. A satellite-derived intensity estimate of 25 kt (13 m/sec) prompted issuance of the first warning at 011200Z November. A week after being first detected, Thelma developed into a tropical storm at 031200Z, and headed west-southwestward for the Philippine island of Samar. Torrential rains dumped an estimated 6 inches (150 mm) of water in 24 hours on the central Philippines before Thelma moved into the South China Sea. The cloud system was unable to reintensify over water due to vertical wind shear (Figure 3-27-1). The final warning was issued at 081200Z as Thelma made landfall over Vietnam's Mekong River Delta.

III. FORECAST PERFORMANCE

Initial track forecasts erroneously predicted recurvature into the westerlies north of the axis of the subtropical ridge (Figure 3-27-2). Objective forecast guidance available at the time when it was most needed to support the warning was split between recurvature and non-recurvature forecasts. In retrospect, the beta advection models showed limited skill in an early prognosis of the west-southwestward motion that occurred from 2 through 6 November.

VI. IMPACT

Thelma was the major catastrophe for the Philippine Islands for 1991 in terms of lost lives, surpassing the Mount Pinatubo eruption. Approximately 6000 people died and 20,000 were left homeless.

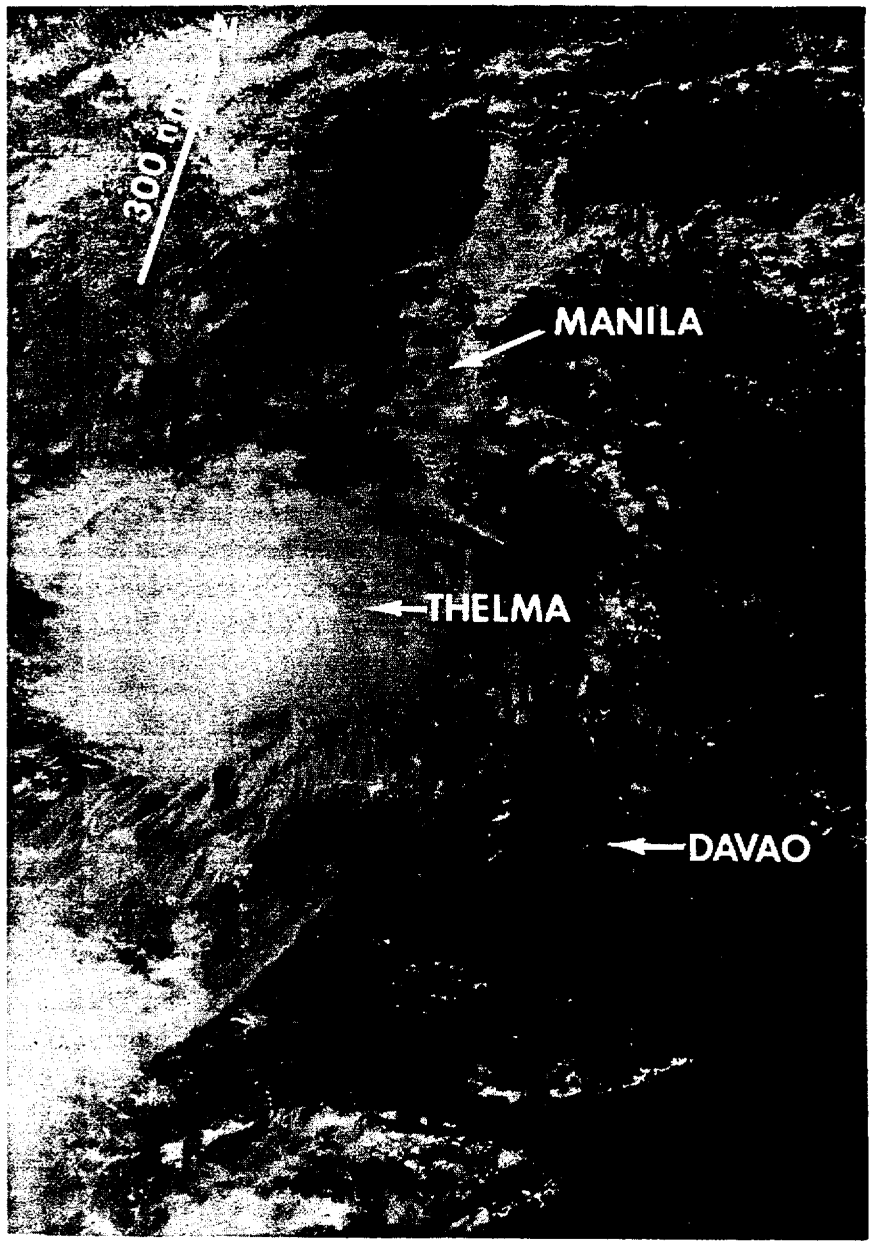


Figure 3-27-1. Thelma enters the South China Sea, but vertical wind shear prevents reintensification (060028Z November DMSP visual imagery).

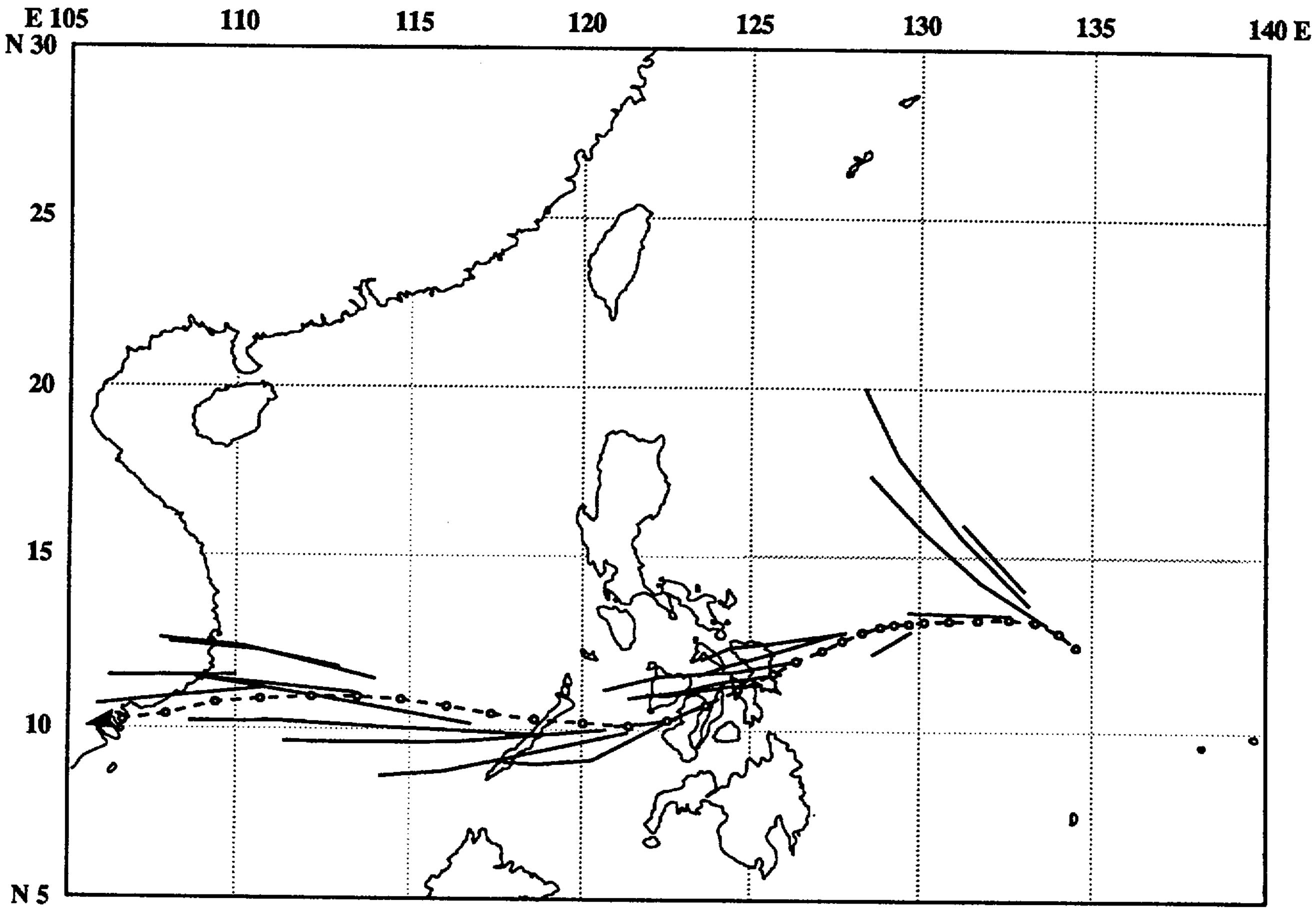
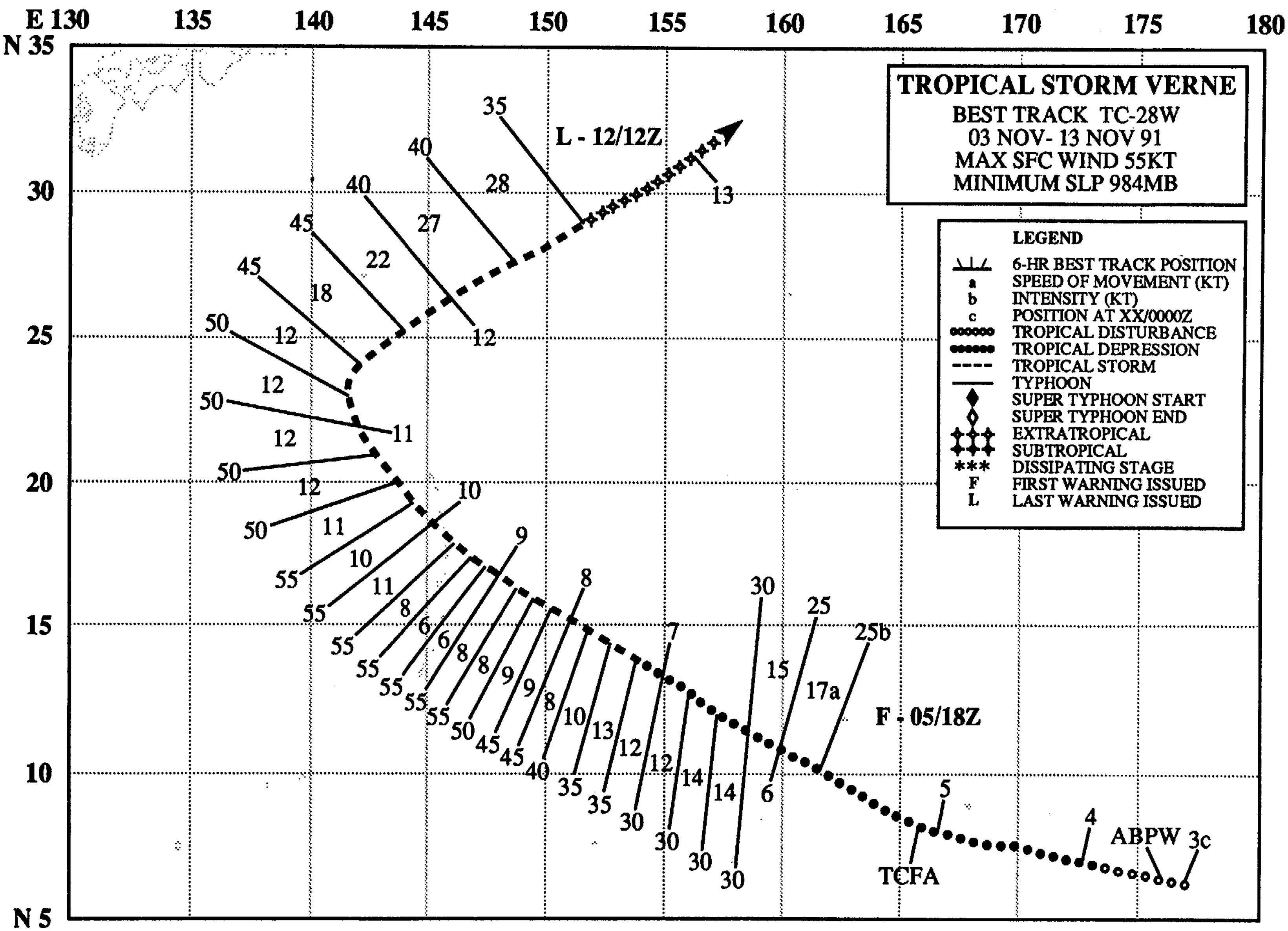


Figure 3-27-2. Comparison of the JTWC official forecasts to the final best track.


TROPICAL STORM VERNE
BEST TRACK TC-28W
03 NOV- 13 NOV 91
MAX SFC WIND 55KT
MINIMUM SLP 984MB
LEGEND
6-HR BEST TRACK POSITION
SPEED OF MOVEMENT (KT)
INTENSITY (KT)
POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
FIRST WARNING ISSUED
LAST WARNING ISSUED
L - 12/12Z
F - 05/18Z
TCFA
ABPW
E 130
135
140
145
150
155
160
165
170
175
180
N 35
30
25
20
15
10
N 5

TROPICAL STORM VERNE (28W)

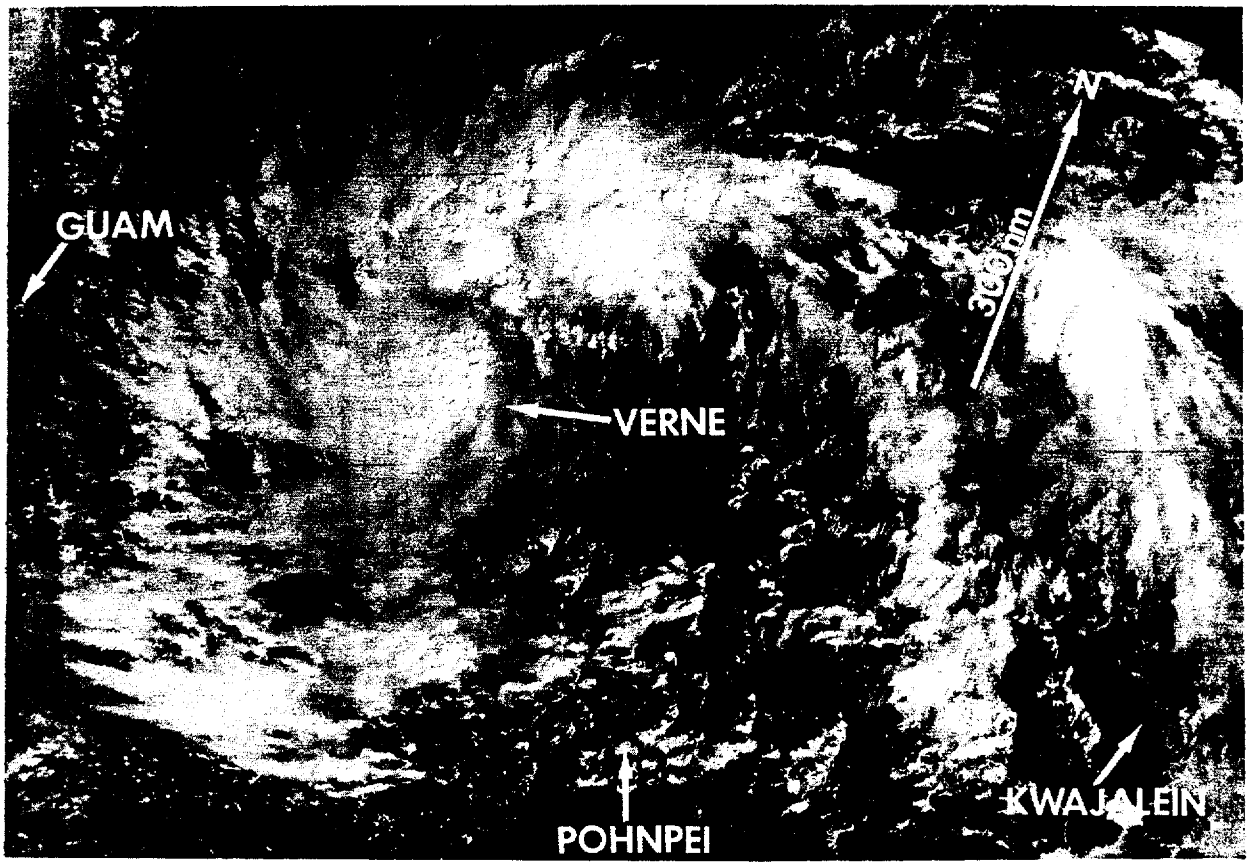
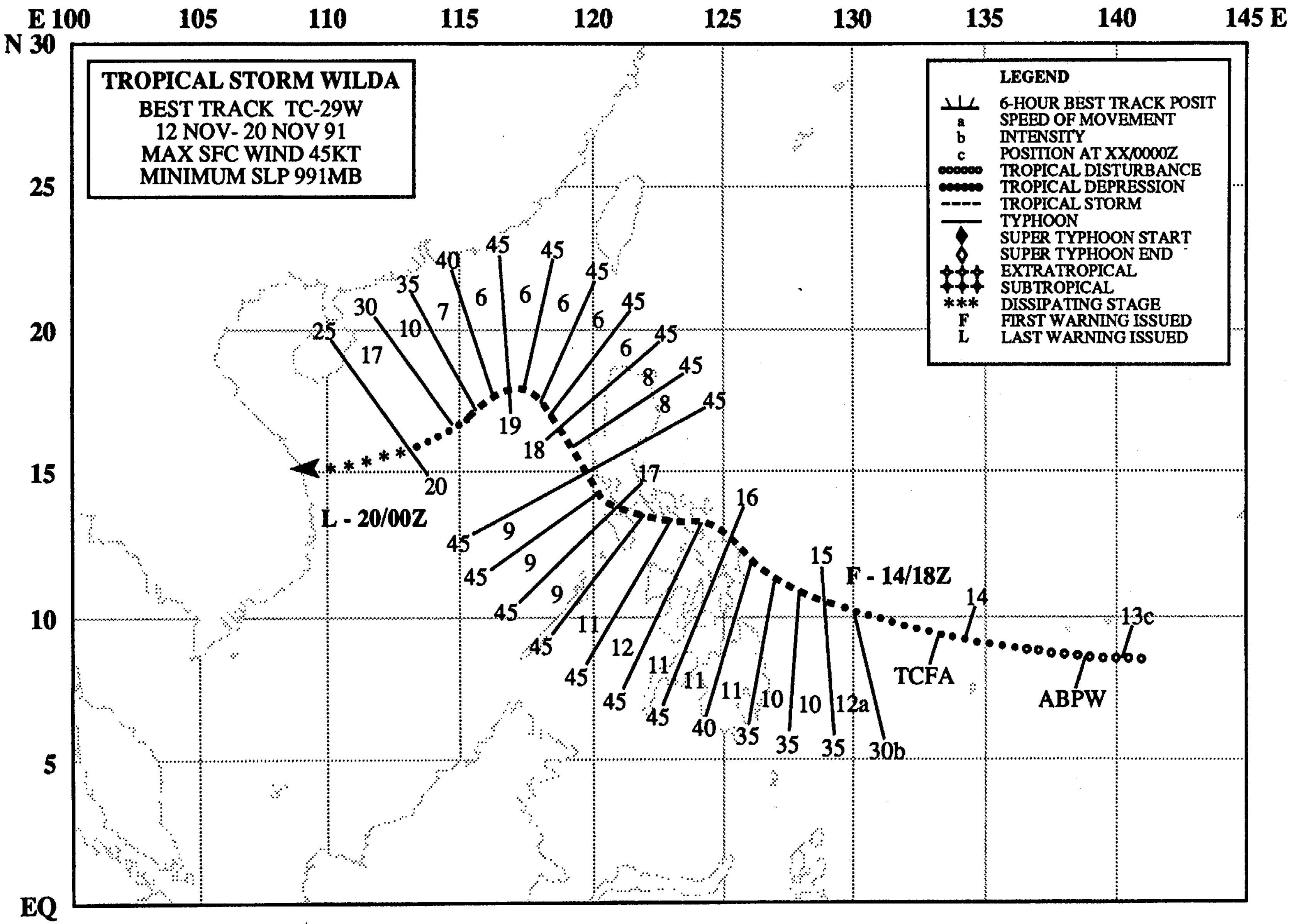


Figure 3-28-1 The partially exposed low-level center of Tropical Storm Verne, located 600 nm (1110 km) east of Guam (062225Z November DMSP visual imagery).

Westerly gradient-level winds along the equator and a persistent cloud system near the international date line on 3 November indicated the potential for further development of a tropical disturbance. Two days after the initial comment about this disturbance on the 030600Z Significant Tropical Weather Advisory, a steady drop of surface pressures in the Marshall Islands convinced forecasters to issue a Tropical Cyclone Formation Alert at 050330Z. Improved convective organization prompted the first warning on Tropical Depression 28W at 051800Z. As the depression tracked west-northwestward, persistent upper-level shear on the east side of the convective cloud mass prevented significant intensification. The shear resulted from a massive upper-level anticyclone located 300 nm (555 km) to the north-northeast of the tropical cyclone. Verne was upgraded to a tropical storm at 071200Z, based on a satellite intensity estimate of 35 kt (18 m/sec). Tropical Storm Verne passed between Pagan and Agrihan Islands in the Northern Marianas with a maximum intensity of 55 kt (28 m/sec), and closed to within 800 nm (1480 km) of Super Typhoon Seth (26W) on 10 November before recurving northeastward on 11 November. The final warning was issued at 121200Z when satellite imagery indicated Verne had transitioned into an extratropical low.


TROPICAL STORM WILDA
BEST TRACK TC-29W
12 NOV- 20 NOV 91
MAX SFC WIND 45KT
MINIMUM SLP 991MB
LEGEND
6-HOUR BEST TRACK POSIT
a SPEED OF MOVEMENT
b INTENSITY
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 100
105
110
115
120
125
130
135
140
145 E
N 30
25
20
15
10
5
EQ
L - 20/00Z
F - 14/18Z
TCFA
ABPW
13c
14
15
16
17
18
19
20
12a
30b

TROPICAL STORM WILDA (29W)

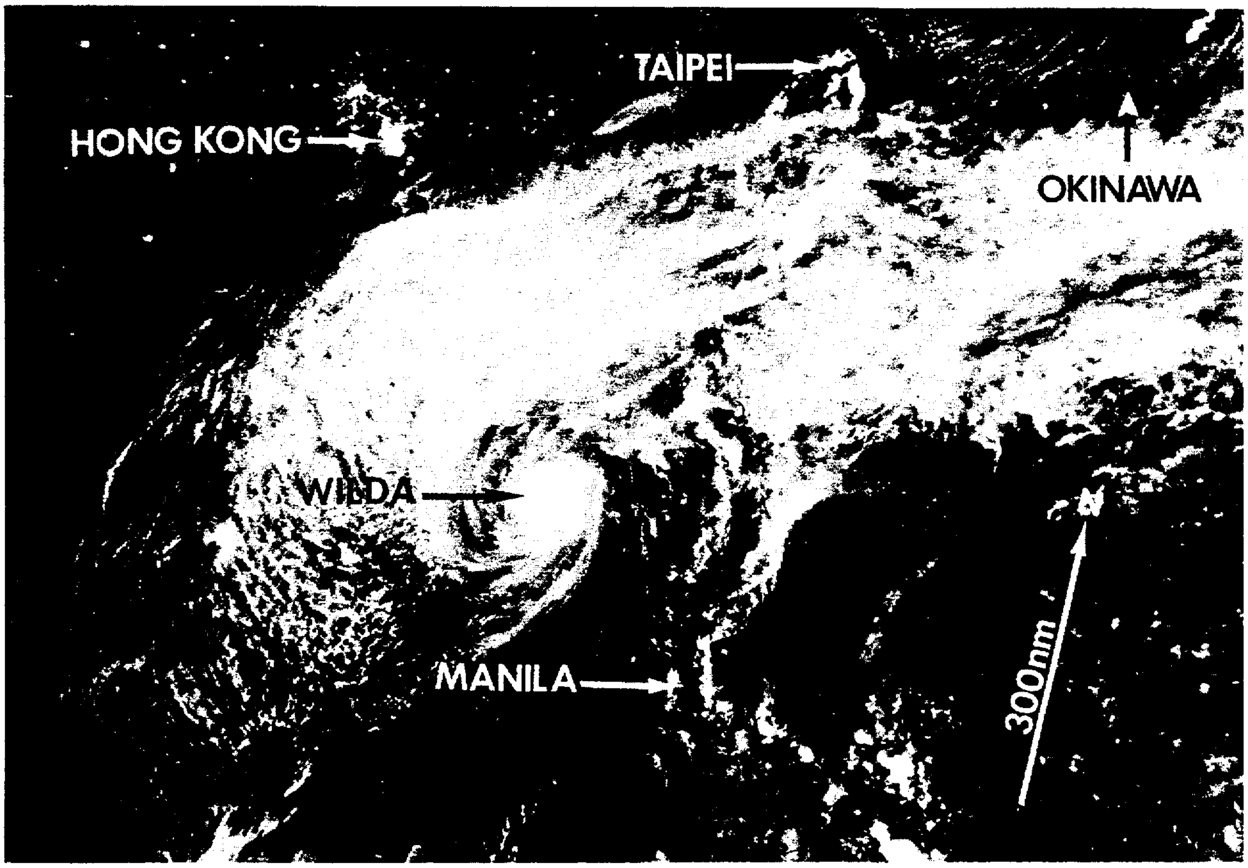
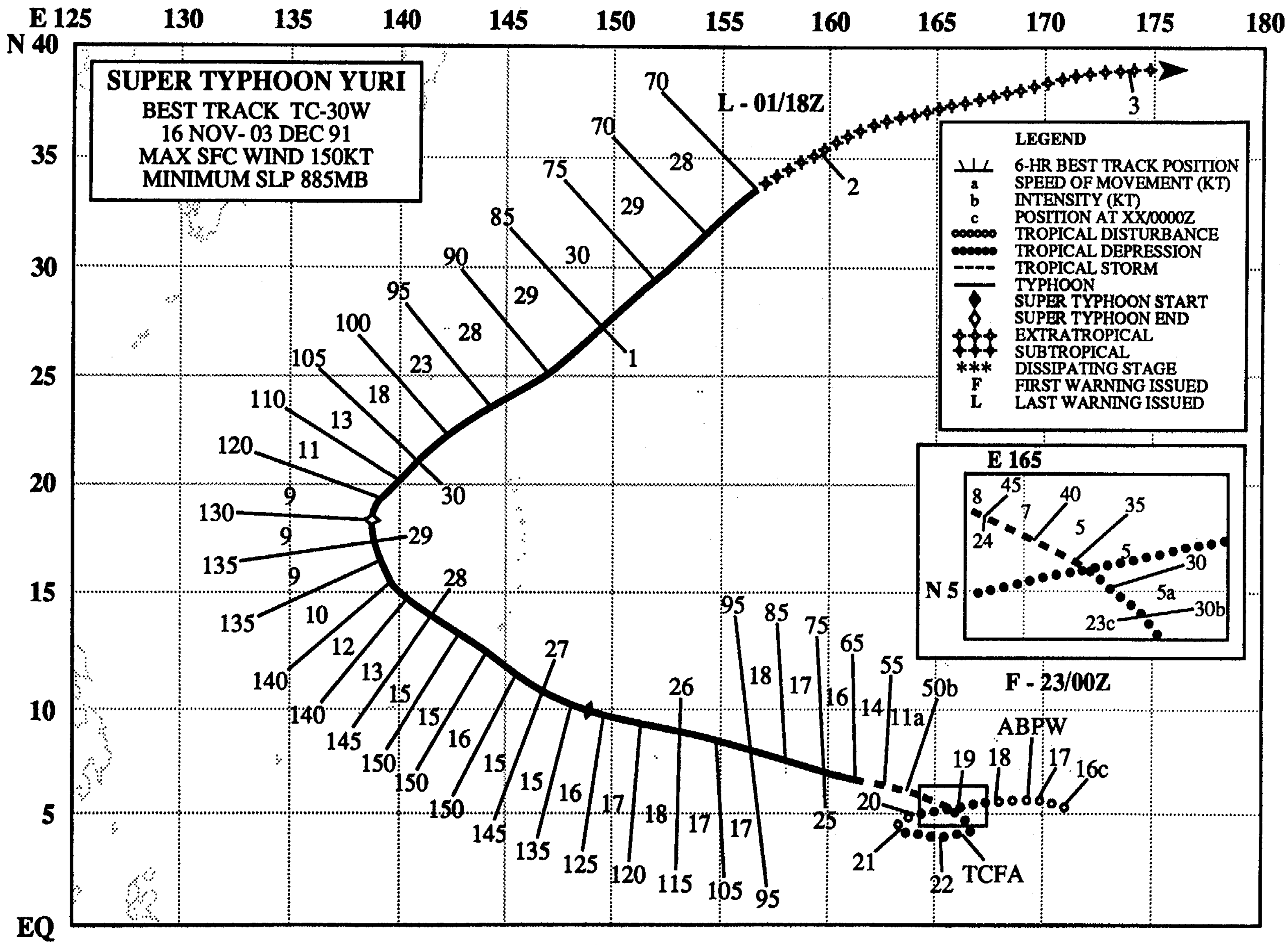


Figure 3-29-1 Tropical Storm Wilda interacts with the northeast monsoon in the South China Sea (181200Z November DMSP moonlight visual imagery).

Tropical Storm Wilda was a midget tropical cyclone, and posed a serious threat to the same central Philippine Islands which were devastated by torrential rains from Tropical Storm Thelma (27W) two weeks earlier. Wilda was initially mentioned on the 130600Z November Significant Tropical Weather Advisory as a small area of persistent deep convection. At 140400Z, JTWC issued a Tropical Cyclone Formation Alert when the system showed a steady increase in convective organization. The first warning followed at 141800Z, based on a Dvorak intensity estimate of 30 kt (15m/s). Wilda continued to intensify as it approached the central Philippines, reaching a peak intensity of 45 kt (23 m/sec) north of Samar. Wilda maintained its peak intensity as it tracked across southern Luzon, passing about 40 nm (75 km) south of Manila at 170400Z. Due to its compact wind field, damage was minimal near Manila. After turning northwestward on 17 November, Wilda began to weaken. The cloud system lost most of its deep convection on 19 November, and the residual low-level circulation drifted southwestward with the prevailing northeast monsoon. The final warning was issued at 200000Z when satellite imagery indicated the system had dissipated.


SUPER TYPHOON YURI
BEST TRACK TC-30W
16 NOV- 03 DEC 91
MAX SFC WIND 150KT
MINIMUM SLP 885MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
L - 01/18Z
F - 23/00Z
ABPW
TCFA
E 165
N 5
E 125
130
135
140
145
150
155
160
165
170
175
180
N 40
35
30
25
20
15
10
5
EQ

SUPER TYPHOON YURI (30W)

I. HIGHLIGHTS

Super Typhoon Yuri was the most intense tropical cyclone of the year, with maximum sustained winds estimated at 150 kt (77 m/sec) and an estimated minimum sea-level pressure of 885 mb. It also was the closest approach to Guam of a cyclone of this intensity since Super Typhoon Karen (1962). Yuri's normal (verses rapid) rate of intensification to a super typhoon was unusual. High water and massive waves caused extensive damage to coastal areas in the southeastern part of Guam.

II. TRACK AND INTENSITY

Low-level westerly winds along the equator extended eastward to the international date line in mid-November. On 16 November, a marked increase in deep convection occurred near 5°N between 160°E and 175°E, and the area was first mentioned on the Significant Tropical Weather Advisory at 170600Z. This tropical disturbance moved slowly westward at about 6°N until it executed a slow counterclockwise loop east of Kosrae in the eastern Caroline Islands between 19 and 23 November. During these five days, convective organization fluctuated about a slow trend toward improved organization. JTWC issued a Tropical Cyclone Formation Alert at 220900Z. The first warning on Tropical Depression 30W was issued at 230000Z, based on a further improvement in convective organization. Twelve hours later, the tropical cyclone was upgraded to a tropical storm when the satellite signature from the Dvorak Technique indicated maximum winds were 35 kt (18 m/sec). Yuri continued to intensify as it accelerated west-northwestward, and reached typhoon intensity 180 nm (335 km) east of Pohnpei at 241800Z. At this time Yuri was about 300 nm (555 km) in diameter, the size of an "average" typhoon. Pohnpei, (WMO 91348) reported a minimum sea-level pressure of 989 mb and a peak wind gust of 64 kt (33 m/sec) when the eye of the typhoon passed 45 nm (85 km) to the north at 250540Z.

On 26 November, as Yuri approached the western periphery of the subtropical ridge axis, it turned slightly toward the northwest and became a super typhoon at 261500Z. The rate of intensification during the 72-hour period from 240600Z to 270600Z was unusual. Unlike most super typhoons which experience an 18- to 30-hour period of rapid or explosive deepening, Yuri's intensity developed steadily at a rate of about 35 kt (18 m/sec) per day. Based on the satellite analyst's current intensity estimate, it reached a peak intensity of 150 kt (77 m/sec) at 270600Z. Yuri grew rapidly in size, reaching 600 nm (1110 km) in diameter, as it approached Guam.

Super Typhoon Yuri posed an extremely serious threat to Guam. Because of its close proximity to the island and a forward motion in excess of 15 kt (28 km/hr), a small change in direction could have rapidly changed the projected closest point of approach to the island resulting in a direct hit with short notice. Fortunately for the people of Guam, the center of the cyclone passed 55 nm (100 km) south of the southern tip of the island. Maximum sustained winds reported on Guam were 80 kt (42 m/sec) with gusts to 100 kt (51 m/sec) in Apra Harbor. The maximum sustained (over water) winds near southern Guam were estimated to be 100 kt (51 m/sec), gusting to 125 kt (64 m/sec).

After passing the Mariana Islands, the super typhoon (Figure 3-30-1) turned northward, and began to slowly weaken as it rounded the western portion of the subtropical ridge. By this time Yuri's size had grown to a massive diameter of 900 nm (1665 km). After its point of recurvature at 290600Z, Yuri was downgraded to a typhoon. North of 20°N latitude, the typhoon accelerated northeastward and gradually transitioned into an intense, late fall extratropical low pressure system. JTWC's final warning was issued on 1 December at 1800Z when satellite imagery revealed a significant decrease in convection near the cyclone's center.

III. FORECAST PERFORMANCE

The sequence of JTWC track forecasts correctly predicted Super Typhoon Yuri would pass south of Guam and follow a typical late season recurvature track by turning northward between 135°E and 140°E (Figure 3-30-2). Early warnings on the tropical cyclone had difficulty predicting

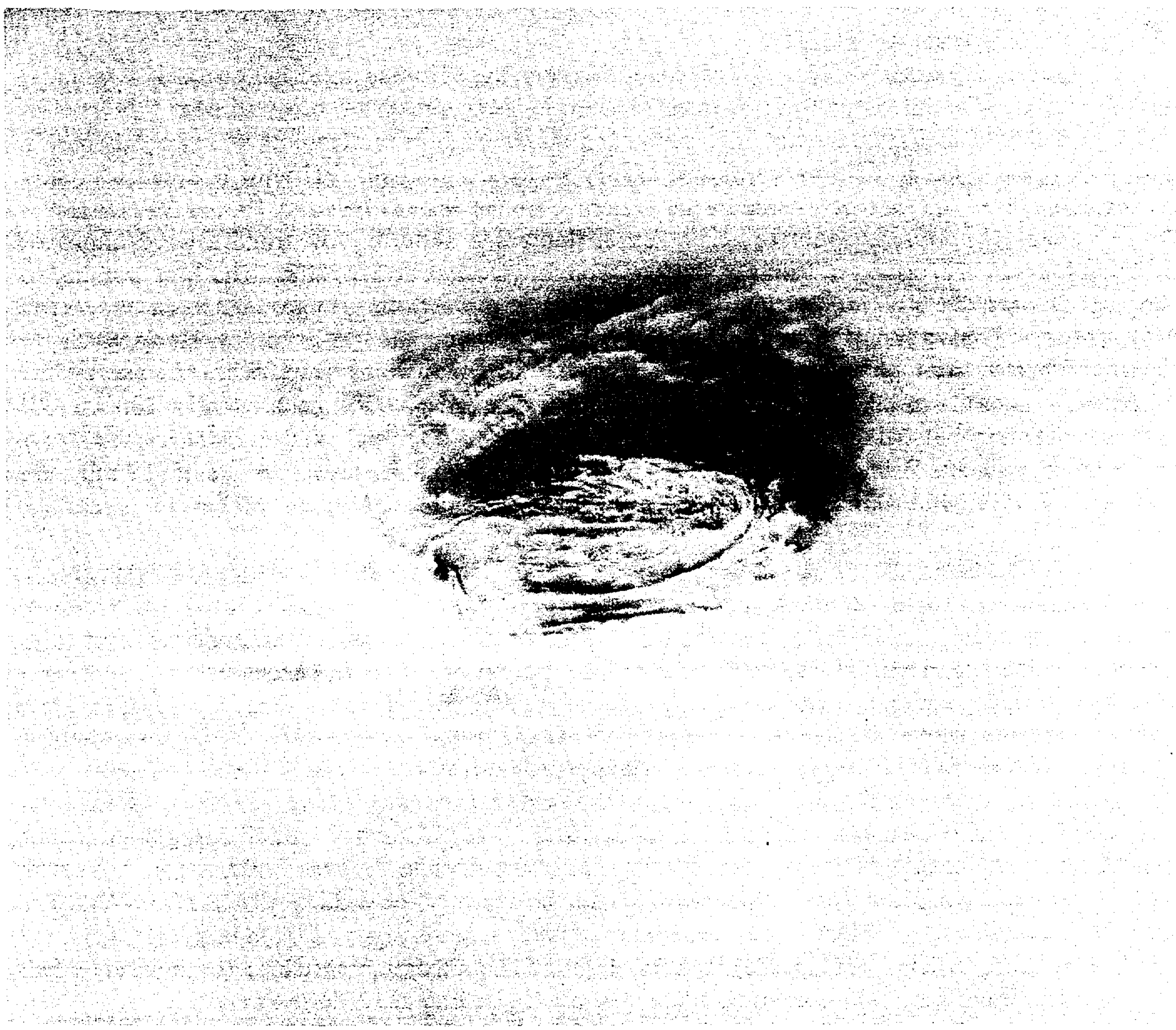


Figure 3-30-1. A spectacular telephoto image from the NASA Space Shuttle Atlantis' mission STS-44 of Super Typhoon Yuri at 145 kt (75 m/sec). Note the cyclonically curved stratocumulus clouds in the high horizontal speed shear zone near the edge of the eye wall (280404Z November photograph courtesy of NASA, Lyndon B. Johnson Space Center, Houston, Texas).

translational motion, since the typhoon accelerated from 5 kt (9 km/hr) on the 23 November to 18 kt (33 km/hr) on 25 November. Although the system continued to accelerate west-northwestward near Pohnpei, JTWC forecast guidance and the warnings based on it, indicated the typhoon would slow as it neared the Marianas. Consequently, early in the week, residents on Guam expected Yuri would make its closest approach on Thanksgiving Day (28 November). Once the forward motion was established, JTWC track forecasts proved to be very accurate as the super typhoon approached Guam. Although JTWC predicted that Yuri would be near super typhoon intensity as it neared Guam, intensity forecasts were a problem. Super typhoon intensity was not expected to occur since the rapid or explosive deepening episode normally associated with super typhoons had not been observed. JTWC also had considerable problems predicting the growth in size of Yuri, as it expanded in size from 300 nm (555 km) to over 900 nm (1665 km) in a little over three days.

Ten hours before Yuri reached its closest point of approach to Guam, NOCC/JTWC recommended that Guam Civil Defense evacuate the southeast coast since inundation exceeding 20 feet (8 m) was expected.

While the forecast performance was only slightly better than average, the warning service provided by NOCC/JTWC was excellent. Yuri's potential to inch closer to Guam, its depiction as an "extremely dangerous storm," and its ability to produce very high waves were passed to residents in hourly updates to the media, convincing people in vulnerable areas to evacuate. This action and the populations appropriate response prevented the loss of lives.

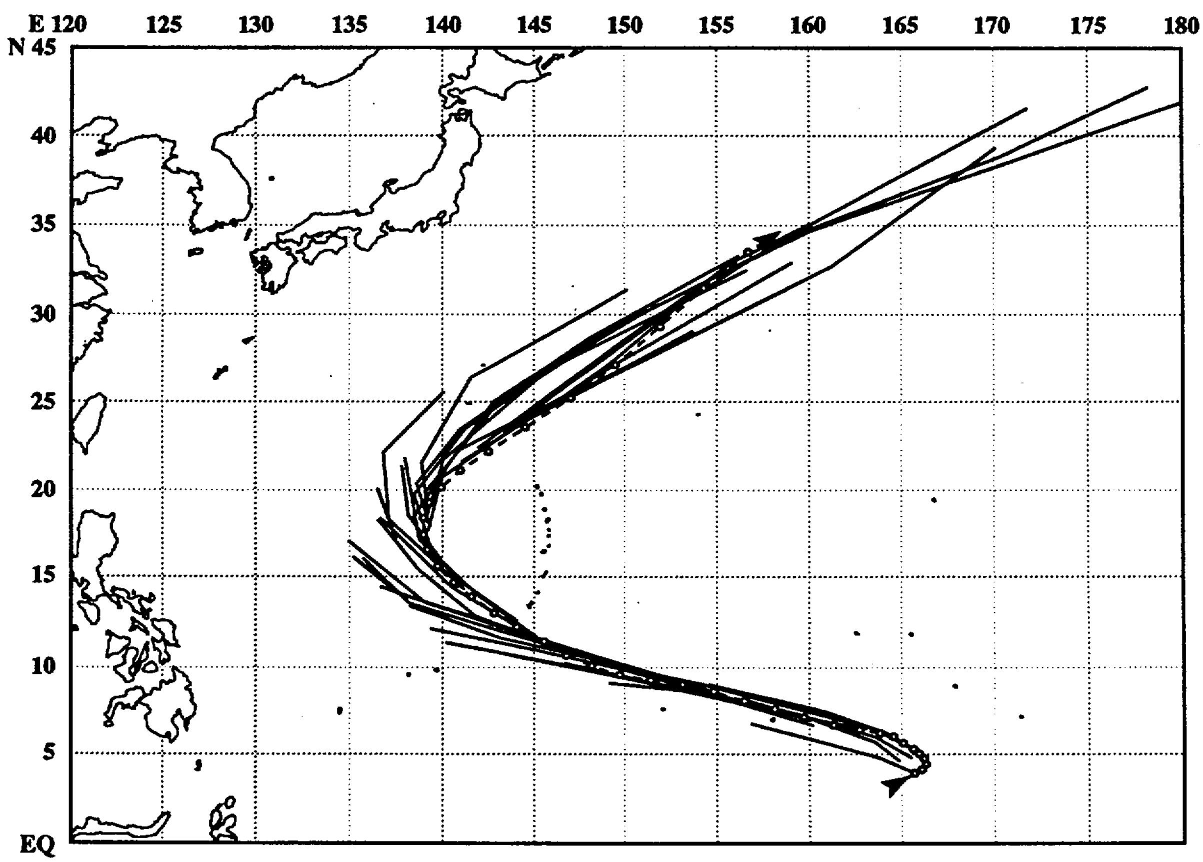


Figure 3-30-2. Summary of JTWC forecasts (solid line) superimposed on Yuri's final best track (dashed line).

IV. IMPACT

An estimated total of $33 million in damage was attributed to Super Typhoon Yuri on Guam, primarily the result of flooding along the southeastern coast. By making its closest point of approach at high tide, the combined effects of a large translational speed, massive size, super typhoon intensity and the cyclone's center location south of Guam exposed the island to a prolonged period of northeasterly winds. This created ideal conditions for extreme surf on the eastern side of the island. Waves in excess of 30 ft (12 m) battered the southeastern coastline. Estimates of high water levels and wave run up at high energy areas with little or no protecting reef flats are shown in Figure 3-30-3. Some of these areas experienced inundation two to three times greater than with Typhoon Russ (1990), 11 months earlier.

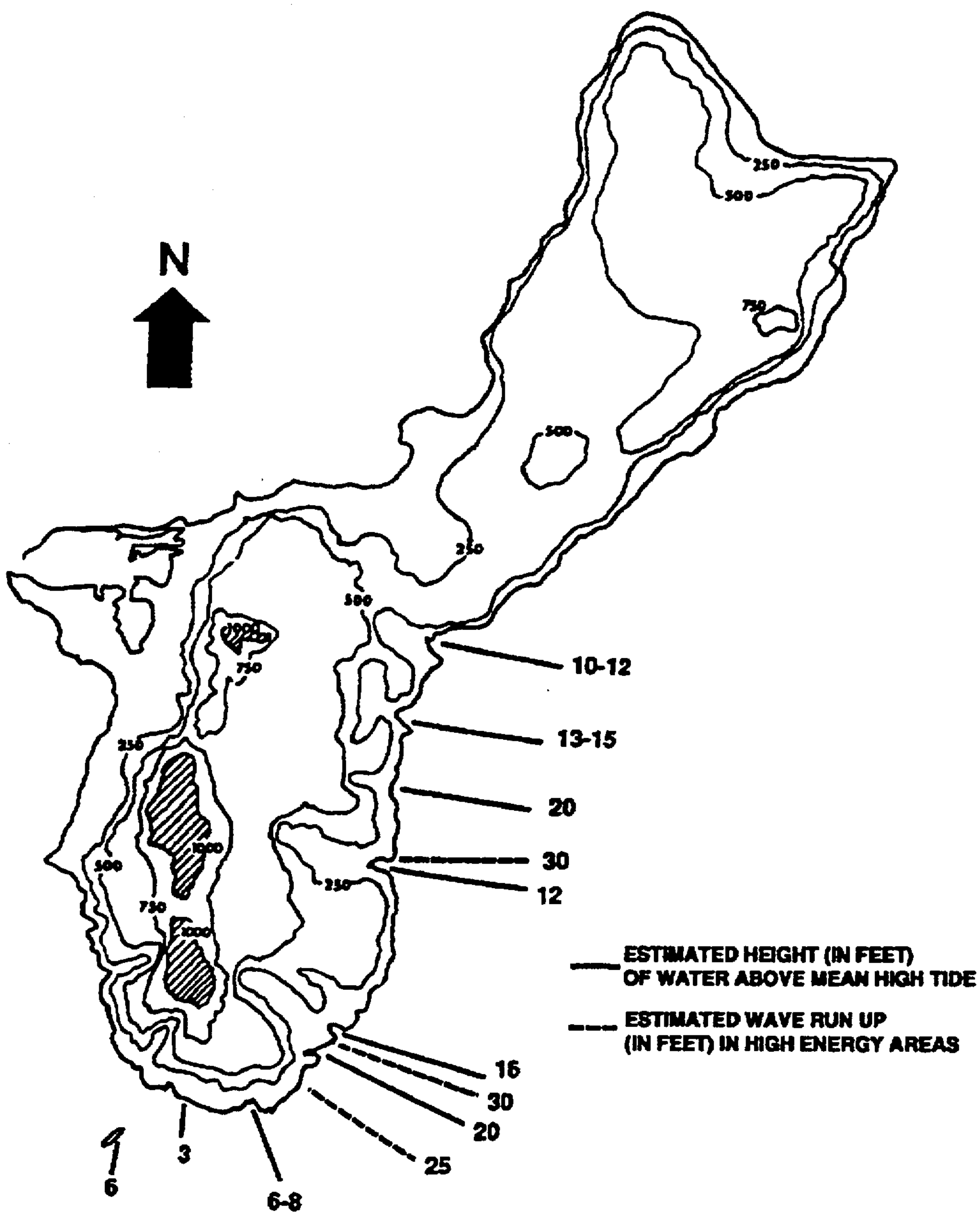
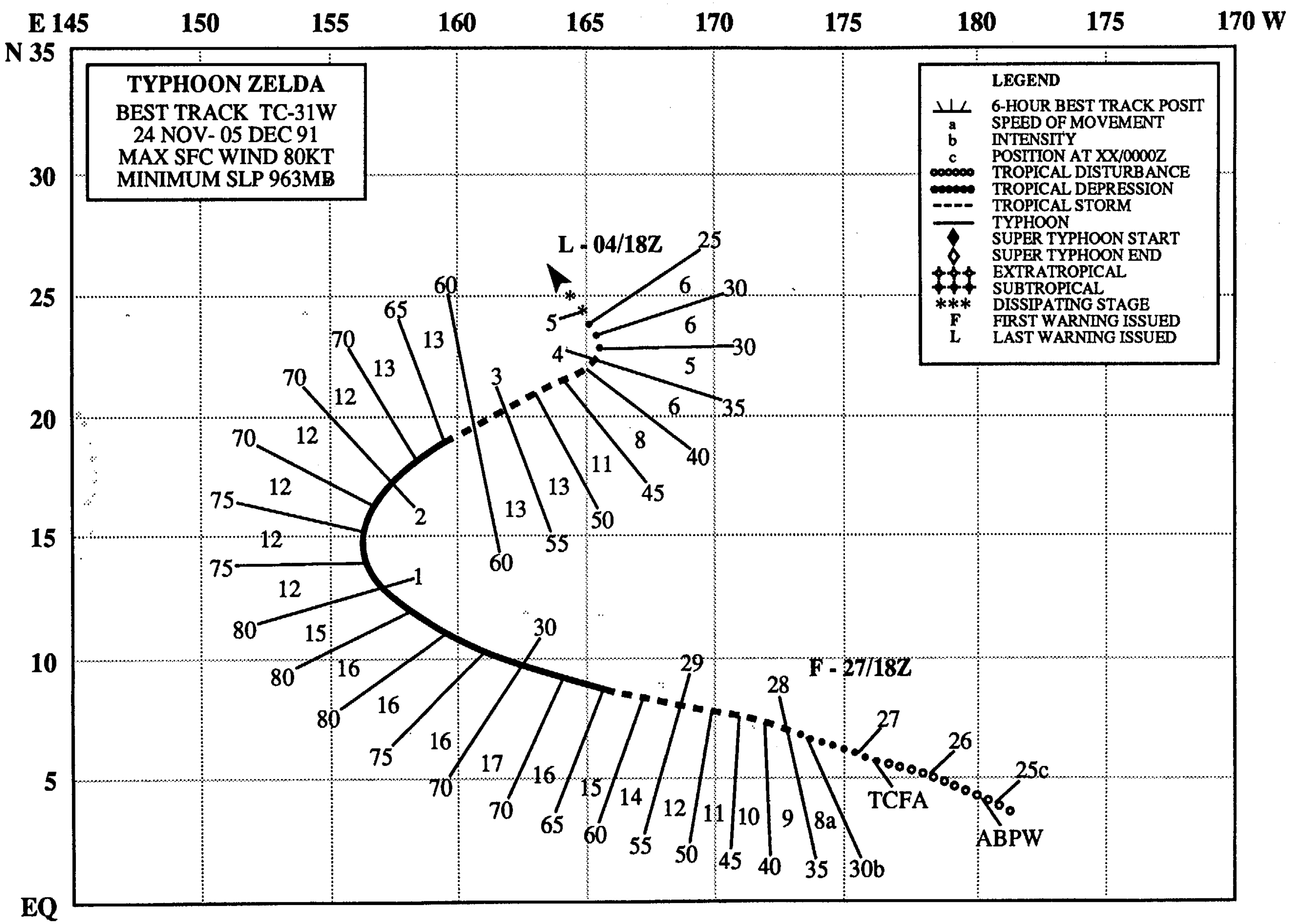


Figure 3-30-3. Estimated water heights above mean high tide and wave run up in the high energy areas of southeastern Guam. Estimated values (in feet) are based on observations taken immediately after tropical cyclone passage.

Yuri's disastrous combination of high water effects caused much greater inundation, reef damage and beach erosion to the island's low-lying beaches and bays along the southeast coastline. Sixty-two homes were totally destroyed; another 207 had major damage; and 348 sustained minor damage. Damage estimates included $19.1 million to public facilities and infrastructure, $10.8 million to commercial buildings and equipment, $2.5 million to residential structures, and $500,000 to agriculture (Figure 3-30-4). Guam residents were without power and water during the Thanksgiving holiday weekend.

Yuri caused an estimated $3 million in damage on Pohnpei, including the loss of the island's only AM radio station tower. Officials on Rota placed damage estimates at $2 million. There was no loss of life in the Marianas or Pohnpei as a result of the cyclone.

Figure 3-30-4. Yuri's high winds uprooted this large tree and parked it on a car. The more flexible, smaller coconut palms in the background survived (Photograph courtesy of Mrs. Patricia L. Hudson).


TYPHOON ZELDA
BEST TRACK TC-31W
24 NOV- 05 DEC 91
MAX SFC WIND 80KT
MINIMUM SLP 963MB
LEGEND
6-HOUR BEST TRACK POSIT
SPEED OF MOVEMENT
INTENSITY
POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 145
150
155
160
165
170
175
180
175
170 W
N 35
30
25
20
15
10
5
EQ
L - 04/18Z
F - 27/18Z
TCFA
ABPW

TYPHOON ZELDA (31W)

I. HIGHLIGHTS

Typhoon Zelda was the last tropical cyclone of the year, and may have set a record by being the fifth midget of the year to occur in the western North Pacific. Intensification during the early stages of its development proved difficult to handle because of its very small size. The operations of the missile test range located at Kwajalein and nearby islands and atolls were seriously affected.

II. TRACK AND INTENSITY

Westerly winds along the equator associated with the onset phase of the El Niño phenomenon helped to generate a weak cyclonic circulation near the international date line in late November. At 250600Z, persistent convection near the weak circulation center that was to become Zelda led to its inclusion on the Significant Tropical Weather Advisory. Strong vertical wind shear initially hampered intensification, but improved upper-level outflow at 262100Z indicated the disturbance had good potential for development, prompting a Tropical Cyclone Formation Alert. At 271800Z, the first warning was issued. Over the next 36 hours, Tropical Depression 31W moved west-northwestward and rapidly intensified to minimal typhoon intensity as it moved through the Marshall Islands. Kwajalein (WMO 91366) reported winds gusting to 71 kt (37 m/sec) as the eye of the midget passed 25 nm (45 km) south of the atoll at 290300Z. Zelda was upgraded to a typhoon at 291200Z based on reports from the Automatic Meteorological Observing Station (AMOS) at Ujae (WMO 91365) which measured sustained surface winds of 65 kt (33 m/sec) (Figure 3-31-1). Zelda continued to track west-northwestward, reaching a peak intensity of 80 kt (41 m/sec) at 301200Z approximately 160 nm (295 km) west of Enewetak. Shortly thereafter, a deep trough induced by Super Typhoon Yuri (30W), which

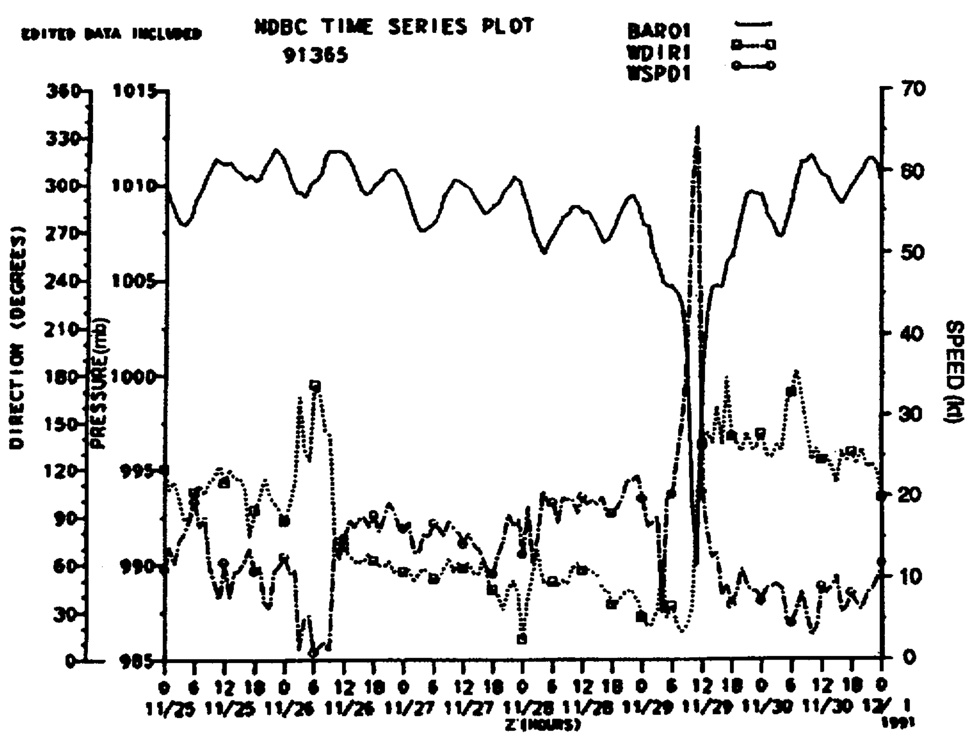


Figure 3-31-1 Time series of wind and pressure observations taken by the Automated Meteorological Observing Station (AMOS) on Ujae Atoll from 250000Z to 302300Z November. Maximum surface winds recorded at 291200Z were 65 kt (33 m/sec), and the minimum pressure dropped to 989 mb (Data courtesy of the National Data Buoy Center).

was about 1000 nm (1850 km) to the northwest, weakened the subtropical ridge, and Zelda turned northward near 157°E (Figure 3-31-2). After recurving, it trailed along a frontal boundary generated by the extratropical remnants of Yuri. As Zelda raced eastward, upper-level winds increased and it's central convection sheared away. The remaining low-level circulation detached from the frontal cloud line and drifted slowly north-northwestward. The final warning on Zelda and the final warning of 1991 was issued on 4 December at 1800Z.

III. FORECAST PERFORMANCE

JTWC's experience with Typhoon Zelda emphasized the difficulties associated with performing infrared satellite analyses of midget tropical cyclones. It underscored the need to use visual and infrared image pairs when available. Due to its small size and seemingly poorly organized outflow pattern, Zelda did not have an impressive infrared satellite signature. Based on a Dvorak intensity estimate of 25 kt (13 m/sec) at 282330Z, the 290000Z warning indicated Zelda was still a tropical depression. But, when radar and synoptic reports from Kwajalein indicated otherwise, the warning was amended to upgrade Zelda to tropical storm intensity. In post-analysis, it is estimated that Zelda actually became a tropical storm at 280000Z, 24 hours earlier and was approaching severe tropical storm intensity as it passed Kwajalein's missile test range, which was caught unprepared by the stronger than forecast winds. Later, Zelda's sharp recurvature track was not anticipated by the JTWC (Figure 3-31-3), and average track forecast errors at 72 hours after 290000Z were 500 nm (925 km).

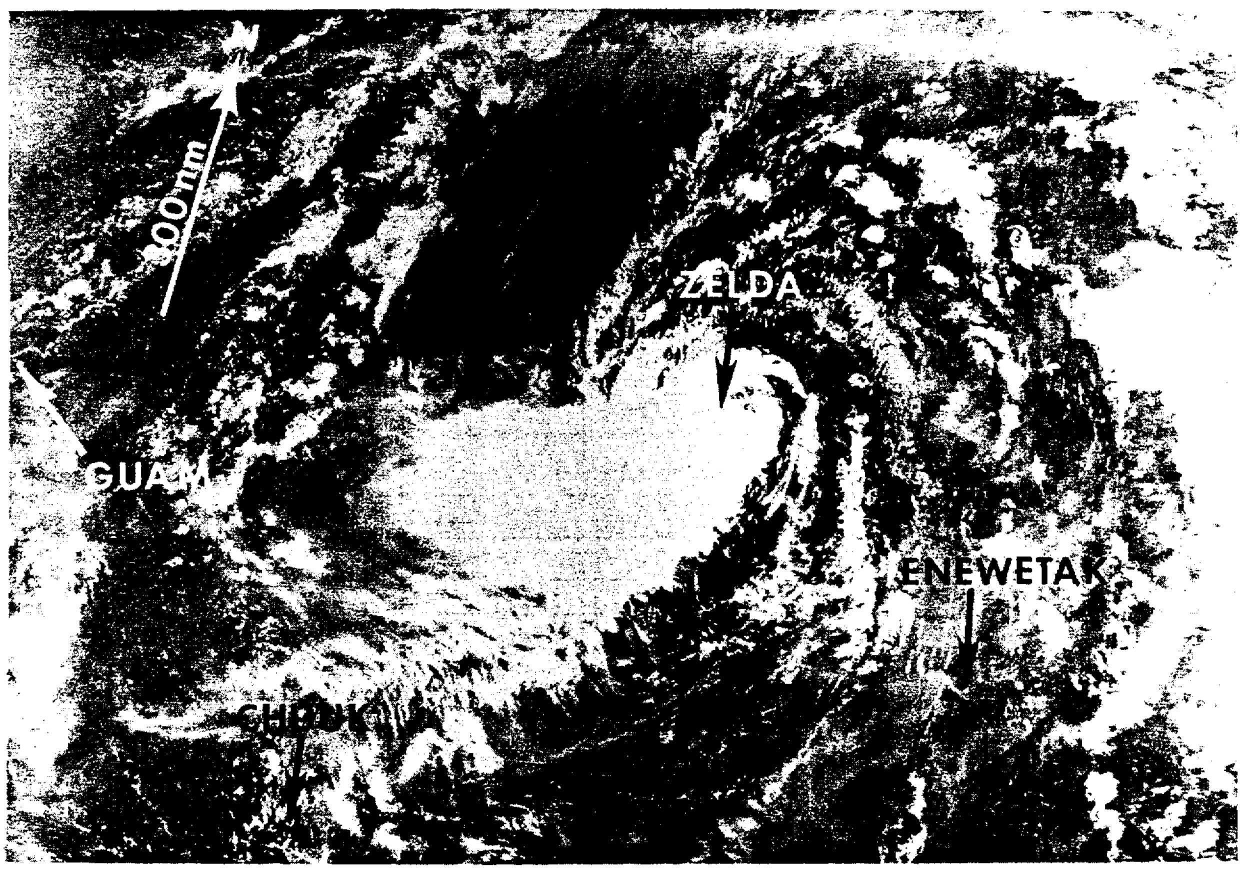


Figure 3-31-2. Typhoon Zelda near its point of recurvature (010903Z December NOAA infrared imagery).

IV. IMPACT

As the Mariana Islands were recovering from giant-sized Super Typhoon Yuri (30W), it was tiny Zelda that left more people homeless and injured. An estimated 5,000 people lost their plyboard and sheet-iron-roofed homes on Ebeye atoll, and 27 people were injured. On 9 December, President Bush signed a major disaster declaration, making Ebeye Island and the atolls of Kwajalein, Lae, and Ujae eligible for federal disaster assistance.

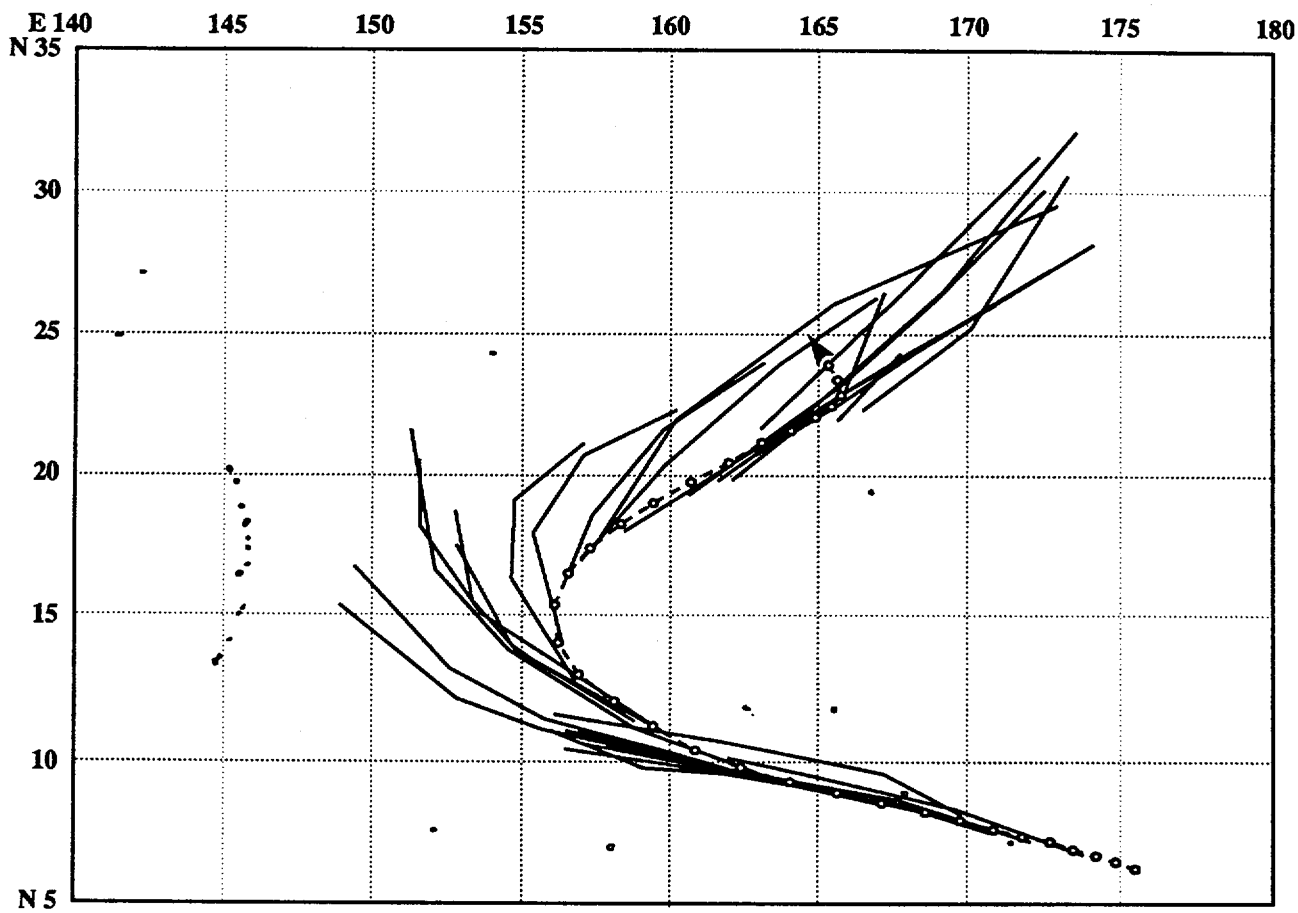


Figure 3-31-3. Comparison of the JTWC official forecasts to the final best track.

3.3 NORTH INDIAN OCEAN TROPICAL CYCLONES

Spring and fall in the North Indian Ocean are periods of transition between major climatic controls and the most favorable seasons for tropical cyclone activity (Tables 3-5 and 3-6). As in 1991, a total of 4 tropical cyclones occurred in the North Indian Ocean, which was close to the long-term average of 4 to 5 per year. The JTWC was in warning status a total of 17 days, and there were no calendar warning days with two or more tropical cyclones.

Tropical Cyclone 01A was a rare January cyclone, the first ever recorded in the Arabian Sea basin. **Tropical Cyclone 02B** was the deadliest and most destructive natural disaster of 1991. A month later, **Tropical Cyclone 03B** caused further damage to the coastline of Bangladesh. In the fall transition season, **Tropical Cyclone 04B** crossed the southern tip of India.

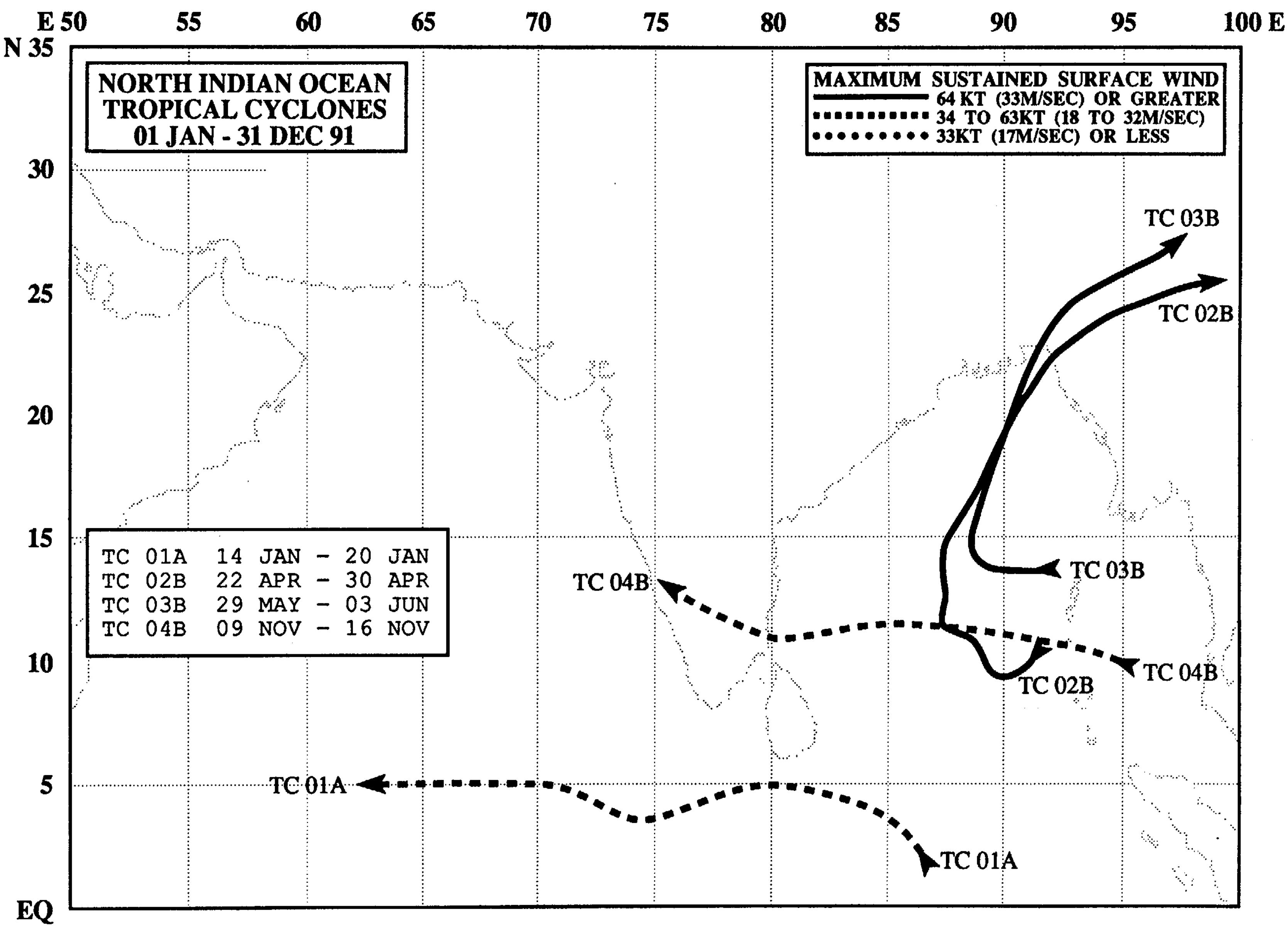
TABLE 3-5. **1991 SIGNIFICANT TROPICAL CYCLONES NORTH INDIAN OCEAN**

TROPICAL CYCLONE	PERIOD OF WARNING	NUMBER OF WARNINGS ISSUED	MAXIMUM SURFACE WINDS-KT (M/SEC)	ESTIMATED MSLP (MB)
TC 01A	17 JAN - 20 JAN	13	35 (18)	997
TC 02B	24 APR - 30 APR	25	140 (72)	898
TC 03B	31 MAY - 02 JUN	10	50 (26)	987
TC 04B	14 NOV - 16 NOV	8	40 (21)	994
	TOTAL:	56		

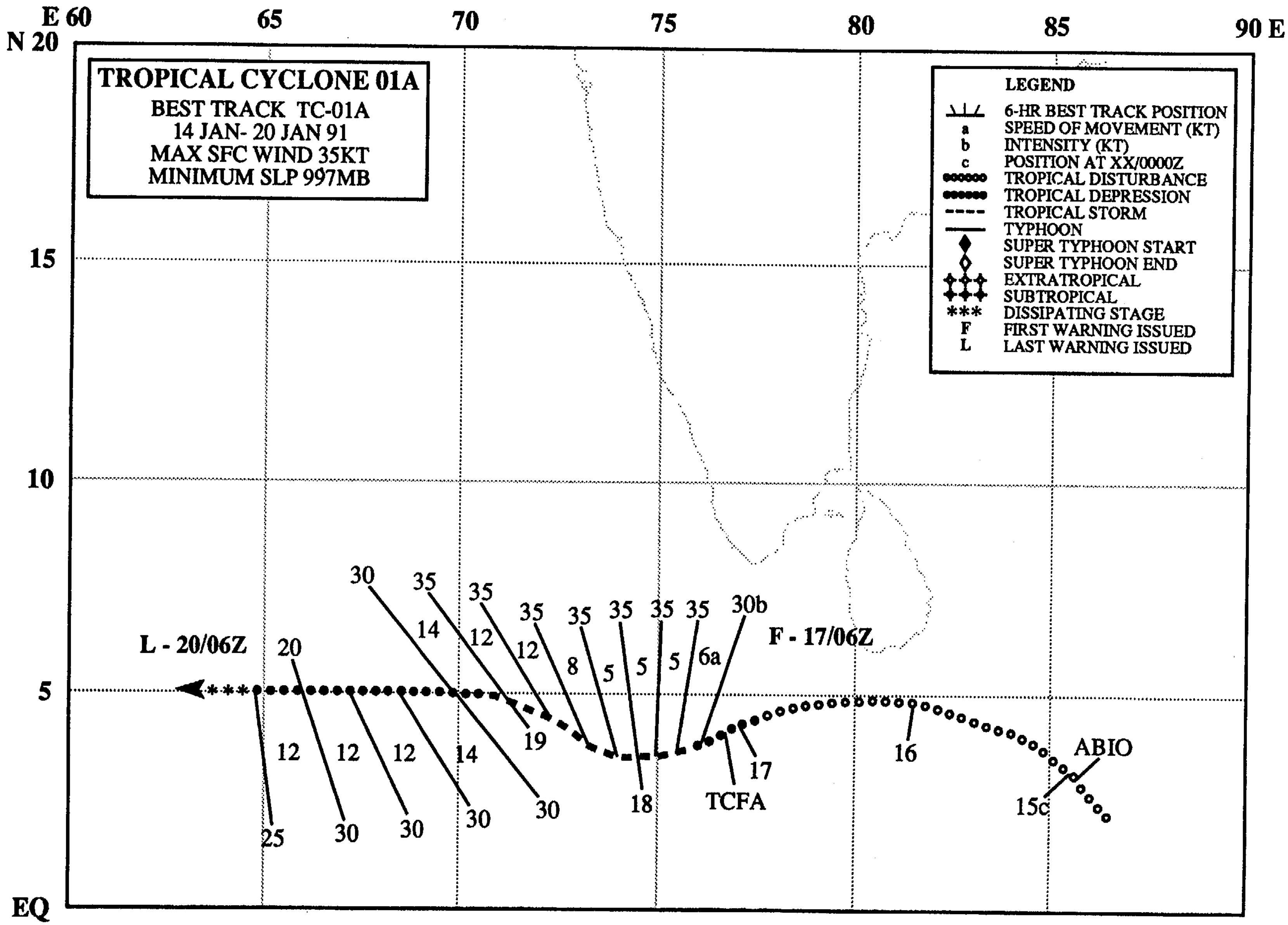
TABLE 3-6. **NORTH INDIAN OCEAN TROPICAL CYCLONES DISTRIBUTION**

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1971*	-	-	-	-	-	0	0	0	0	1	1	0	2
1972*	0	0	0	1	0	0	0	0	2	0	1	0	4
1973*	0	0	0	0	0	0	0	0	0	1	2	1	4
1974*	0	0	0	0	0	0	0	0	0	0	1	0	1
1975	1	0	0	0	2	0	0	0	0	1	2	0	6
1976	0	0	0	1	0	1	0	0	1	1	0	1	5
1977	0	0	0	0	1	1	0	0	0	1	2	0	5
1978	0	0	0	0	1	0	0	0	0	1	2	0	4
1979	0	0	0	0	1	1	0	0	2	1	2	0	7
1980	0	0	0	0	0	0	0	0	0	0	1	1	2
1981	0	0	0	0	0	0	0	0	0	1	1	1	3
1982	0	0	0	0	1	1	0	0	0	2	1	0	5
1983	0	0	0	0	0	0	0	1	0	1	1	0	3
1984	0	0	0	0	1	0	0	0	0	1	2	0	4
1985	0	0	0	0	2	0	0	0	0	2	1	1	6
1986	1	0	0	0	0	0	0	0	0	0	2	0	3
1987	0	1	0	0	0	2	0	0	0	1	2	2	8
1988	0	0	0	0	0	1	0	0	0	1	2	1	5
1989	0	0	0	0	1	1	0	0	0	0	1	0	3
1990	0	0	0	1	1	0	0	0	0	0	1	1	4
1991**	1	0	0	1	0	1	0	0	0	0	1	0	4
(1975-1991) AVERAGE:	0.2	0.1	0.0	0.2	0.6	0.5	0.0	0.1	0.2	0.8	1.4	0.5	4.5
TOTAL:	3	1	0	3	11	9	0	1	3	14	24	8	77

* JTWC WARNING RESPONSIBILITY BEGAN ON 4 JUNE 1971 FOR THE BAY OF BENGAL, EAST OF 90° EAST LONGITUDE. AS DIRECTED BY CINCPAC, JTWC ISSUED WARNINGS ONLY FOR THOSE TROPICAL CYCLONES THAT DEVELOPED OR TRACKED THROUGH THAT PART OF THE BAY OF BENGAL. IN 1975, JTWC'S AREA OF RESPONSIBILITY WAS EXTENDED WESTWARD TO INCLUDE THE WESTERN PART OF THE BAY OF BENGAL AND THE ENTIRE ARABIAN SEA.



NORTH INDIAN OCEAN
TROPICAL CYCLONES
01 JAN - 31 DEC 91
MAXIMUM SUSTAINED SURFACE WIND
64 KT (33M/SEC) OR GREATER
34 TO 63KT (18 TO 32M/SEC)
33KT (17M/SEC) OR LESS
TC 01A 14 JAN - 20 JAN
TC 02B 22 APR - 30 APR
TC 03B 29 MAY - 03 JUN
TC 04B 09 NOV - 16 NOV
E 50
55
60
65
70
75
80
85
90
95
100 E
N 35
30
25
20
15
10
5
EQ
TC 03B
TC 02B
TC 03B
TC 04B
TC 04B
TC 02B
TC 01A
TC 01A


TROPICAL CYCLONE 01A
BEST TRACK TC-01A
14 JAN- 20 JAN 91
MAX SFC WIND 35KT
MINIMUM SLP 997MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
E 60
65
70
75
80
85
90 E
N 20
15
10
5
EQ
L - 20/06Z
F - 17/06Z
ABIO
TCFA
15c
16
17
18
19
20
30b
6a

TROPICAL CYCLONE 01A

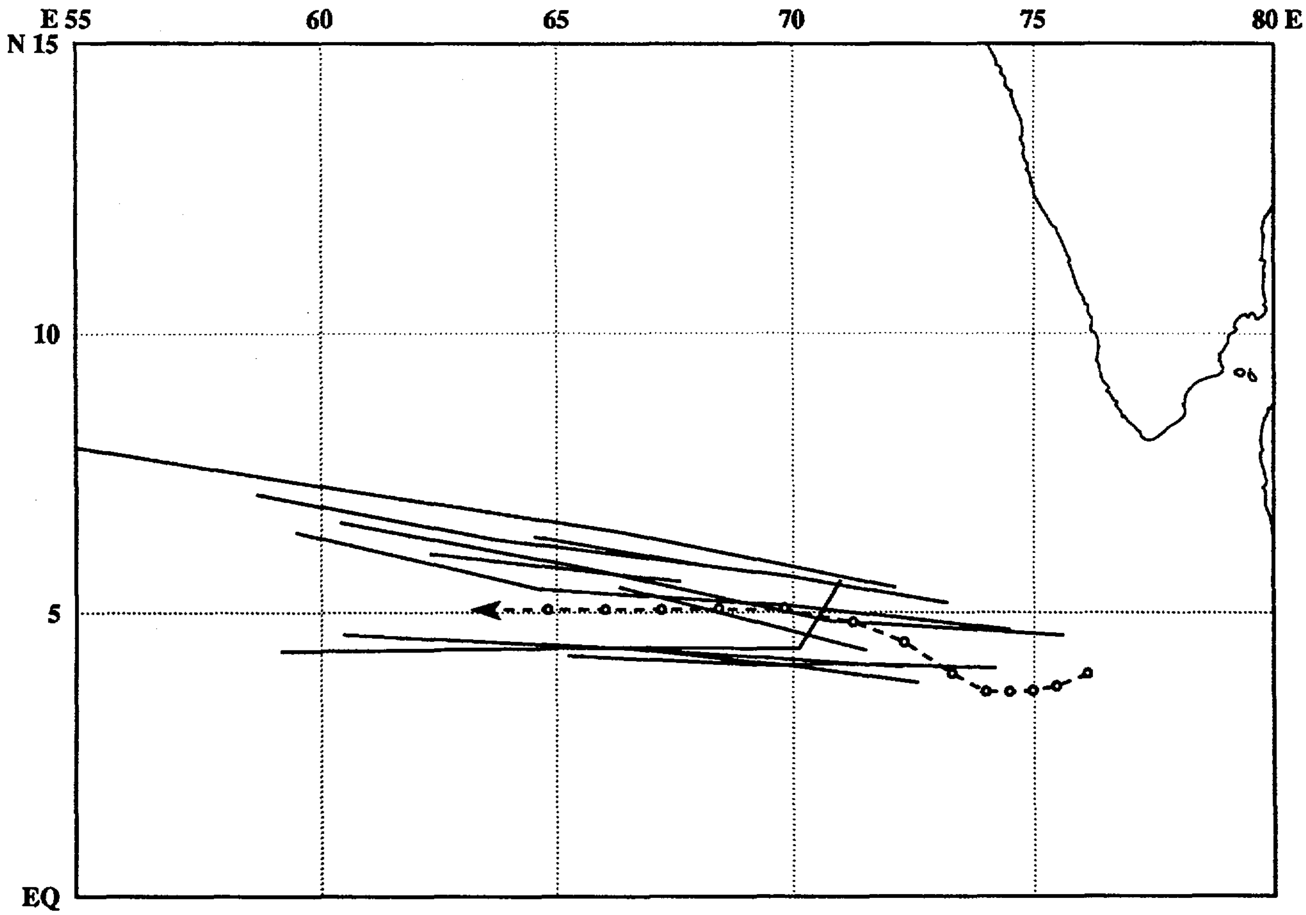
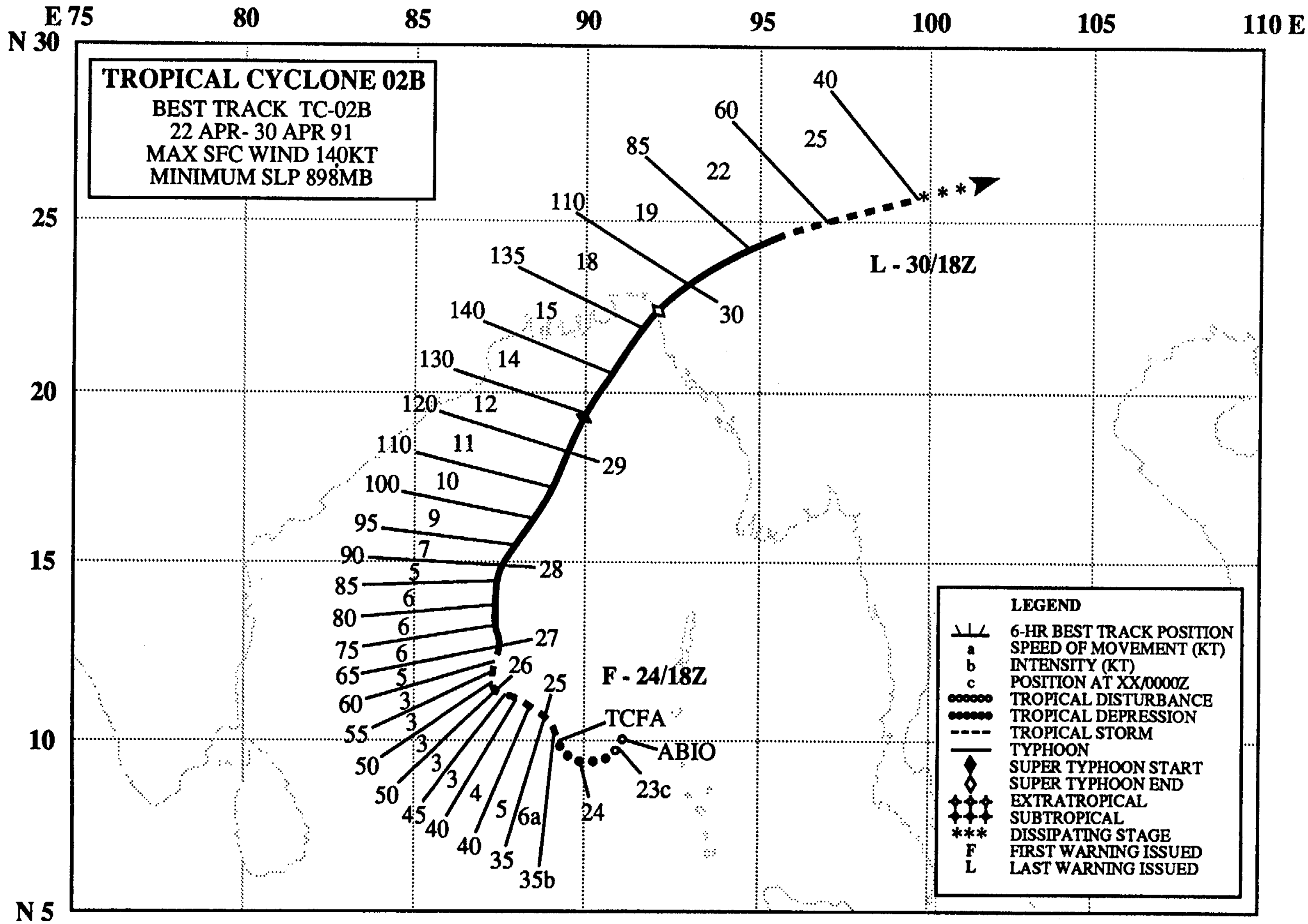


Figure 3-01A-1. On the same day that hostilities erupted in the Persian Gulf, an area of organized convection persisted near Sri Lanka. Because this area posed a potential threat to Allied forces operating in the Arabian Sea, Persian Gulf and the Red Sea, and the 141800Z January Significant Tropical Weather Advisory was reissued at 142300Z. A steady increase in convection which indicated that the disturbance was intensifying, prompted a Tropical Cyclone Formation Alert at 170300Z. The first warning followed at 170600Z. Tropical Cyclone 01A tracked westward under a narrow subtropical ridge, and failed to intensify past minimal tropical storm intensity due to strong vertical wind shear. Strong upper-level winds stripped most of the deep convection away from the center on 18 January, and the remaining low-level circulation slowly dissipated in the Arabian Sea. The final warning was issued at 200600Z.

Although Tropical Cyclone 01A was the first tropical cyclone to develop during January in the Arabian Sea through the past 20 years of record, it was not a significant factor in the Persian Gulf build-up. Because of its low-latitude track and weak intensity, it had little effect on ships steaming to the Middle East. A summary of JTWC forecasts versus the official best track shows the difficulty in positioning the poorly defined cloud system center, producing the large scatter of initial warning positions.


TROPICAL CYCLONE 02B
BEST TRACK TC-02B
22 APR- 30 APR 91
MAX SFC WIND 140KT
MINIMUM SLP 898MB
E 75
80
85
90
95
100
105
110 E
N 30
25
20
15
10
N 5
L - 30/18Z
F - 24/18Z
TCFA
ABIO
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
*** DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TROPICAL CYCLONE 02B

I. HIGHLIGHTS

Tropical Cyclone 02B was the deadliest and most destructive natural disaster of 1991. It occurred nineteen years after an estimated 300,000 lives were lost in a similar cyclone which struck the low-lying Ganges River delta region of Bangladesh. On April 29 and 30, 1991, Tropical Cyclone 02B (TC 02B) devastated the coastal city of Chittagong (located 115 nm (210 km) southeast of the capital city of Dacca) and the surrounding area with winds in excess of 130 kt (65 m/sec) and a 20-foot (6 m) storm surge. The official death toll was estimated at 138,000, and the damage at US$1.5 billion. The death toll might have been higher than that in 1970, but according to newspaper reports an estimated 2 to 3 million people were evacuated from the coastal region prior to the onset of destructive winds and massive storm surge. A survey of survivors by researchers from the Centers for Disease Control based in Atlanta, Georgia indicated the major reason that many people did not heed the warnings was that they did not believe the cyclone would be as severe as forecast.

II. TRACK AND INTENSITY

On 22 April, westerly winds and persistent cloudiness in the equatorial regions of the North Indian Ocean spawned a large cyclonic circulation which became evident in the synoptic data and satellite imagery over the southern Bay of Bengal. By 24 April, the cloud mass associated with the circulation encompassed nearly the entire Bay of Bengal. Ships reported that surface winds had increased to over 30 kt (15 m/sec). These data prompted the issuance of a Tropical Cyclone Formation Alert at 241400Z. The first warning followed shortly afterward at 241800Z when the tropical cyclone showed signs of rapid development. Steady intensification continued as TC 02B passed through the axis of the subtropical ridge on 27 April and recurved. On 28 April, acceleration started due to the influence of stronger mid-level southwesterlies. The southwesterlies aloft also enhanced upper-level outflow, and TC02B rapidly intensified into a rare Bay of Bengal cyclone of super typhoon intensity (Figure 3-02B-1). At landfall, the center of the eye of TC 02B passed 30 nm (55 km) south of Chittagong at 291900Z. Official reports stated that the destructive fury lasted eight hours in Chittagong. As the tropical cyclone weakened rapidly over the mountainous terrain inland, its torrential rains caused extensive flooding in the region.

III. FORECAST PERFORMANCE

Initial JTWC track forecasts moved TC 02B slowly northwestward toward the east coast of India as the subtropical high over India retreated westward. However, the mid-trospospheric subtropical high located to the east of the system over central Thailand remained fixed and acted as the primary steering mechanism. The cyclone tracked slowly northward between that subtropical high and the high over India. After 271800Z, JTWC anticipated that recurvature would in fact occur, and subsequent warnings indicated that TC 02B would strike the coast of Bangladesh (Figure 3-02B-2). The actual point of landfall near Cittagong on the coast of Bangladesh was correctly forecast after the 281200Z warning, 31 hours prior to landfall .

The first few JTWC forecasts indicated that TC 02B would track slowly northwestward and intensify before making landfall in eastern India. JTWC forecasters anticipated significant development because of the combination of weak vertical wind shear and strong speed divergence aloft, both north and south of the cyclone. On the 280600Z warning, JTWCs predictions indicated the tropical cyclone would cross the coast of Bangladesh at an intensity of about 100 kt (50 m/sec). Commencing with the warning at 290000Z, JTWC intensity rationale changed as the Center forecast that the maximum sustained surface winds at landfall would exceed 120 kt (60 m/sec) due to anticipated continued rapid intensification.

IV. IMPACT

In terms of storm surge, the Bay of Bengal is the most dangerous tropical cyclone basin in the World. Not only are the physical characteristics of the basin conducive to producing very large storm surges, but the low lying coastal areas are heavily populated. In addition to the tremendous loss of life due to TC02B, ten million people, one-tenth of the population of Bangladesh, were displaced as an estimated one million homes were destroyed. The human suffering associated with this event was staggering.

Communicating by telephone, JTWC kept the U.S. Embassy in Dacca informed of the cyclone's expected track and characteristics for the 48-hour period prior to it hitting land. This communication squelched rumors that the cyclone would strike the Dacca-Ganges delta region of Bangladesh, and probably prevented an unnecessary evacuation of Embassy personnel.

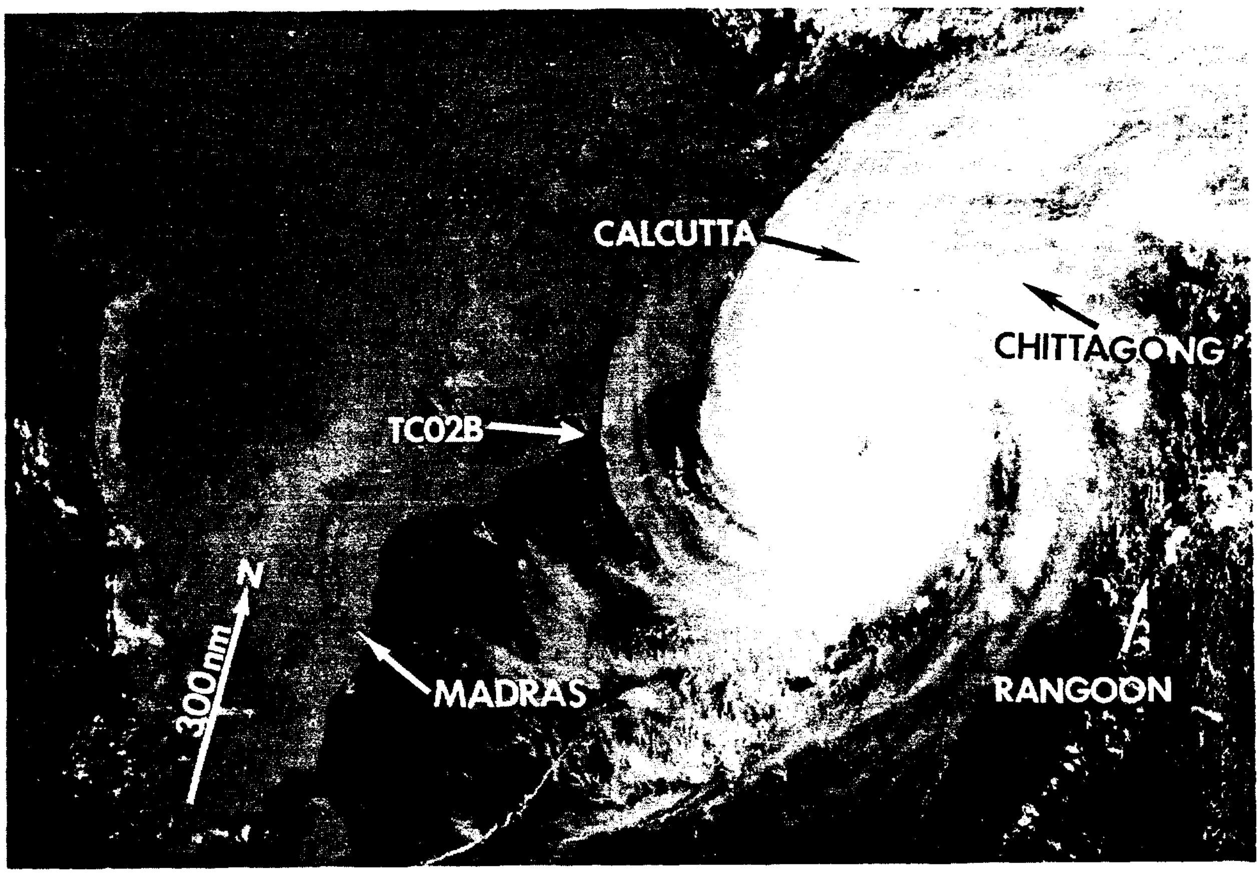


Figure 3-02B-1. TC02B with winds in excess of 130 kt (65 m/sec) bears down on the coast of Bangladesh (28 April DMSP visual imagery).

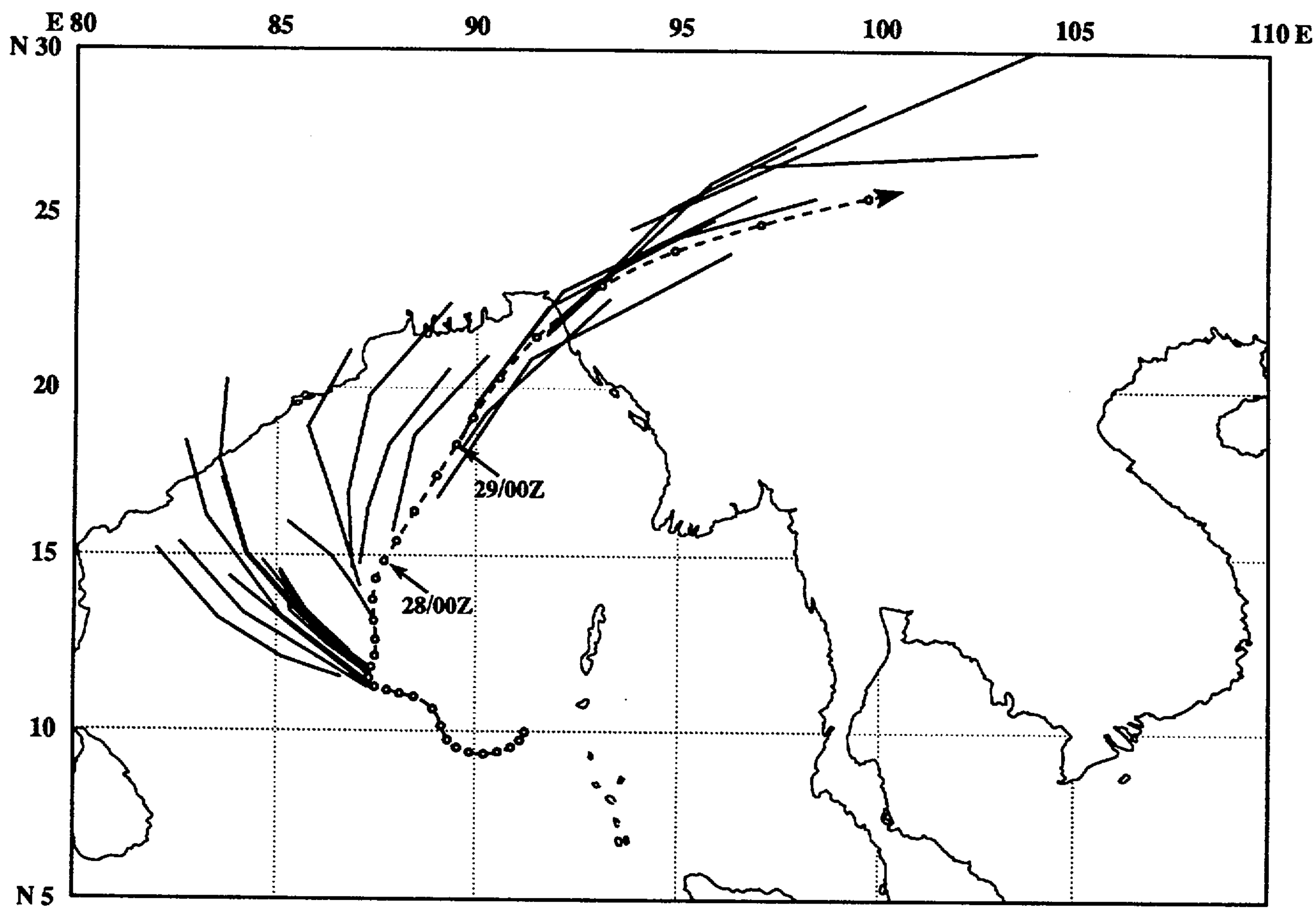
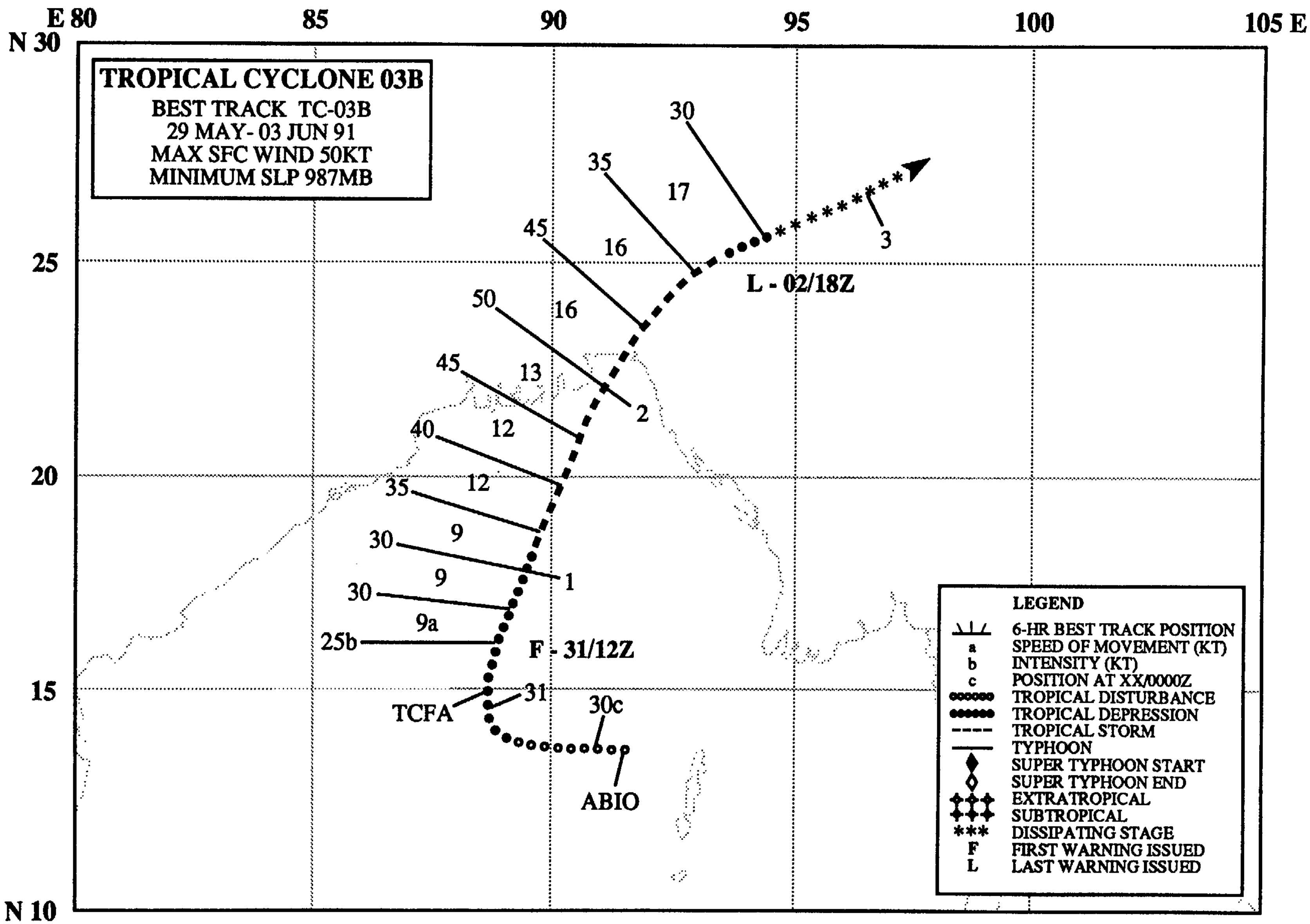


Figure 3-02B-2. Summary of JTWC forecasts (solid lines) for TC02B superimposed on the best track (dashed line).


TROPICAL CYCLONE 03B
BEST TRACK TC-03B
29 MAY- 03 JUN 91
MAX SFC WIND 50KT
MINIMUM SLP 987MB
E 80
85
90
95
100
105 E
N 30
25
20
15
N 10
L - 02/18Z
F - 31/12Z
TCFA
ABIO
30c
31
1
2
3
25b
9a
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED

TROPICAL CYCLONE 03B

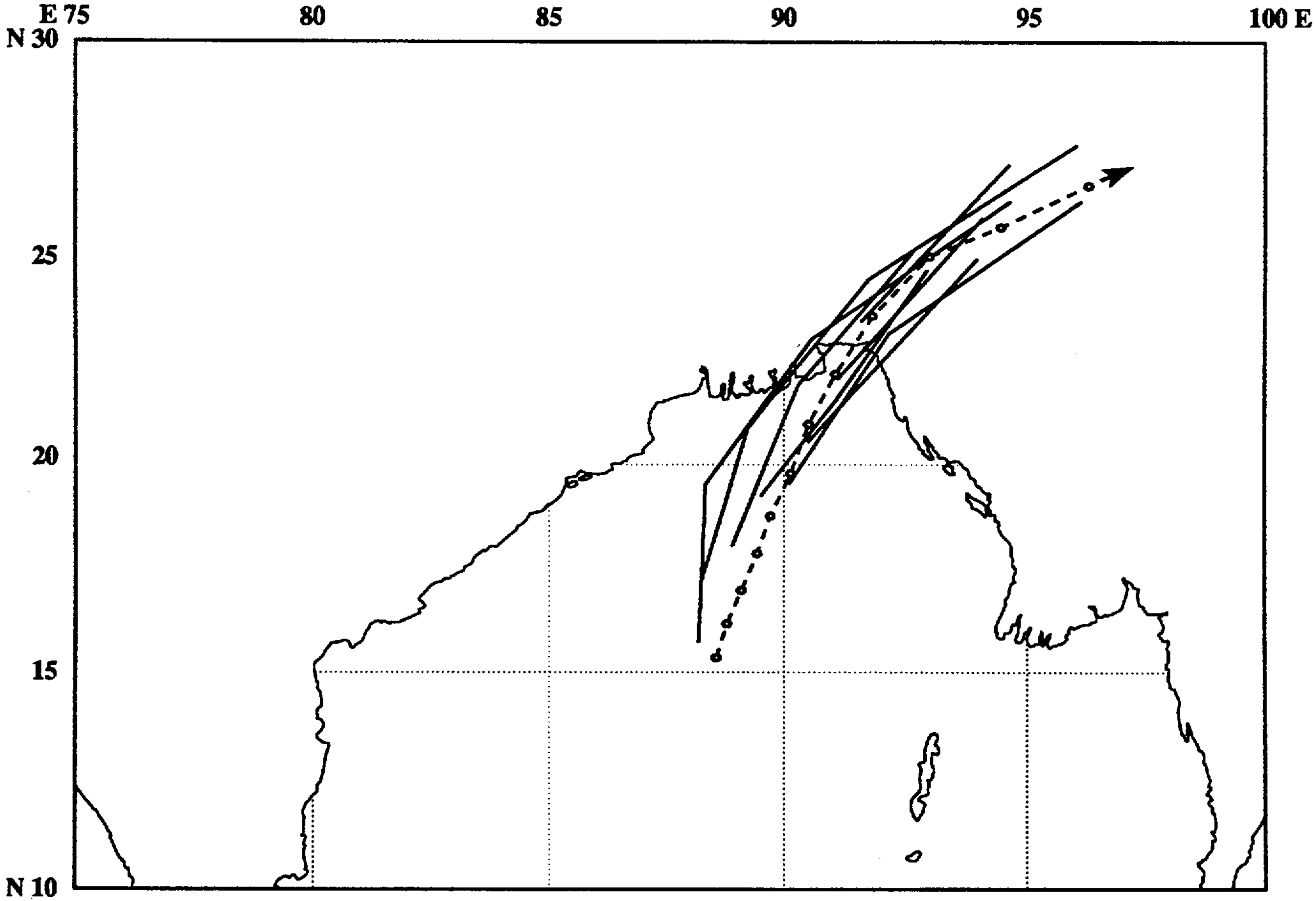
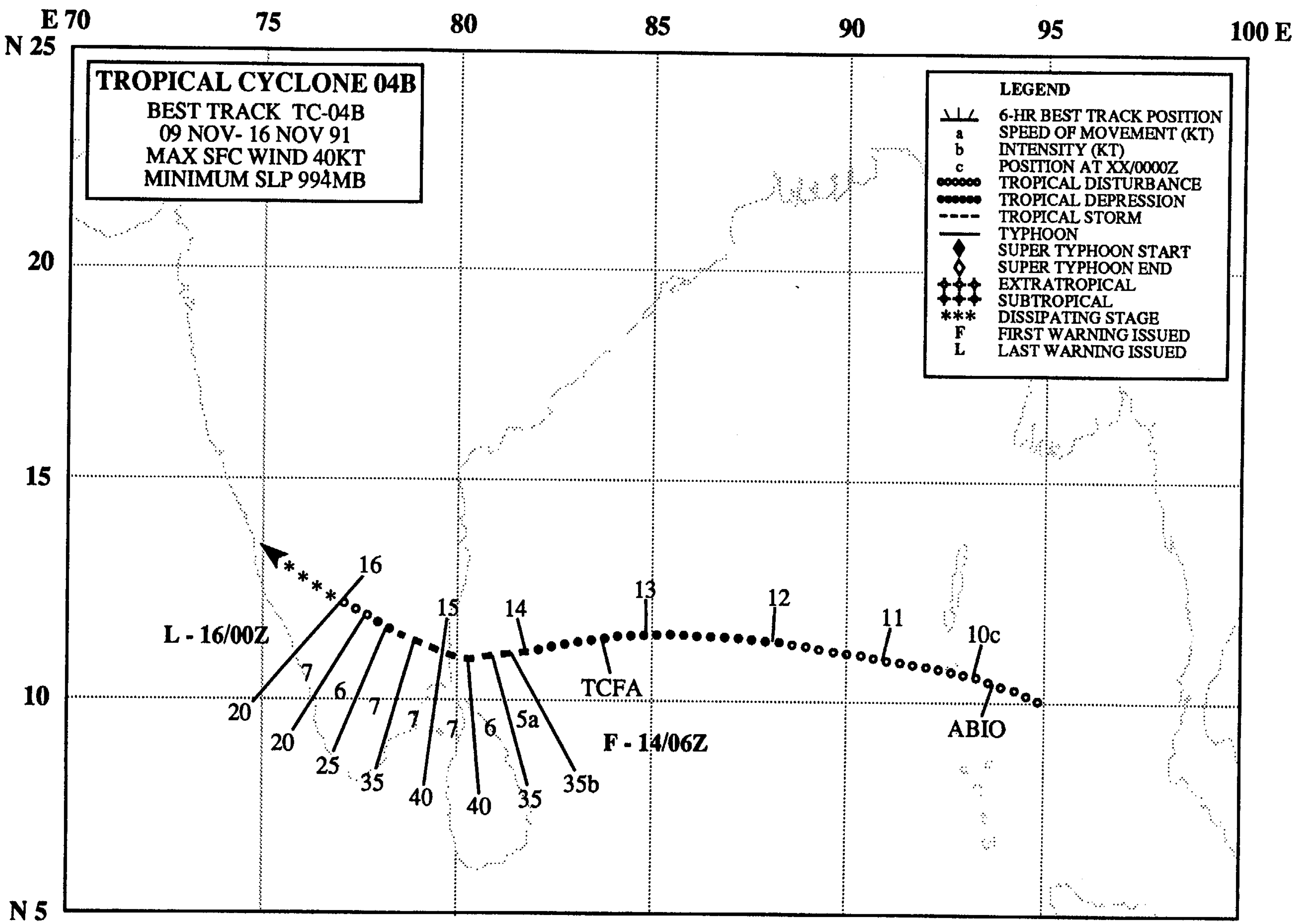


Figure 3-03B-1. In the aftermath of the devastation due to Tropical Cyclone 02B, another destructive weather system, Tropical Cyclone 03B, struck the same coastline of Bangladesh one month later, and caused further damage. Cyclone 03B was initially mentioned on the 291800Z May Significant Tropical Weather Advisory as a weak, poorly organized low-level circulation. Over the next 30 hours, it gradually intensified and tracked westward. As the system began to move northward and gain convective organization, a Tropical Cyclone Formation Alert was issued at 310030Z followed by the first warning at 311200Z. Tropical Cyclone 03B reached its peak intensity of 50 kt (25 m/sec) shortly before landfall, midway between Dacca and Chittagong on the coast of Bangladesh at 020400Z, after which it rapidly dissipated over mountainous terrain inland. The final warning was issued at 021800Z.

The cyclone caused minor flooding in Bangladesh and disrupted the relief efforts of Operation SEA ANGEL by forcing the amphibious cargo ship, **USS St. Louis**, to seek room to maneuver offshore. Tropical Cyclone 03B's impact on SEA ANGEL was minimized by accurate track and intensity forecasts, and by up-to-the-minute information provided to decision makers by JTWC forecasters. A comparison of JTWC forecasts to the final best track is provided.



E 70
75
80
85
90
95
100 E
N 25
20
15
10
N 5
TROPICAL CYCLONE 04B
BEST TRACK TC-04B
09 NOV- 16 NOV 91
MAX SFC WIND 40KT
MINIMUM SLP 994MB
LEGEND
6-HR BEST TRACK POSITION
a SPEED OF MOVEMENT (KT)
b INTENSITY (KT)
c POSITION AT XX/0000Z
TROPICAL DISTURBANCE
TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON
SUPER TYPHOON START
SUPER TYPHOON END
EXTRATROPICAL
SUBTROPICAL
DISSIPATING STAGE
F FIRST WARNING ISSUED
L LAST WARNING ISSUED
16
15
14
13
12
11
10c
L - 16/00Z
TCFA
F - 14/06Z
ABIO
7
6
7
7
7
6
5a
20
20
25
35
40
40
35
35b

160

TROPICAL CYCLONE 04B

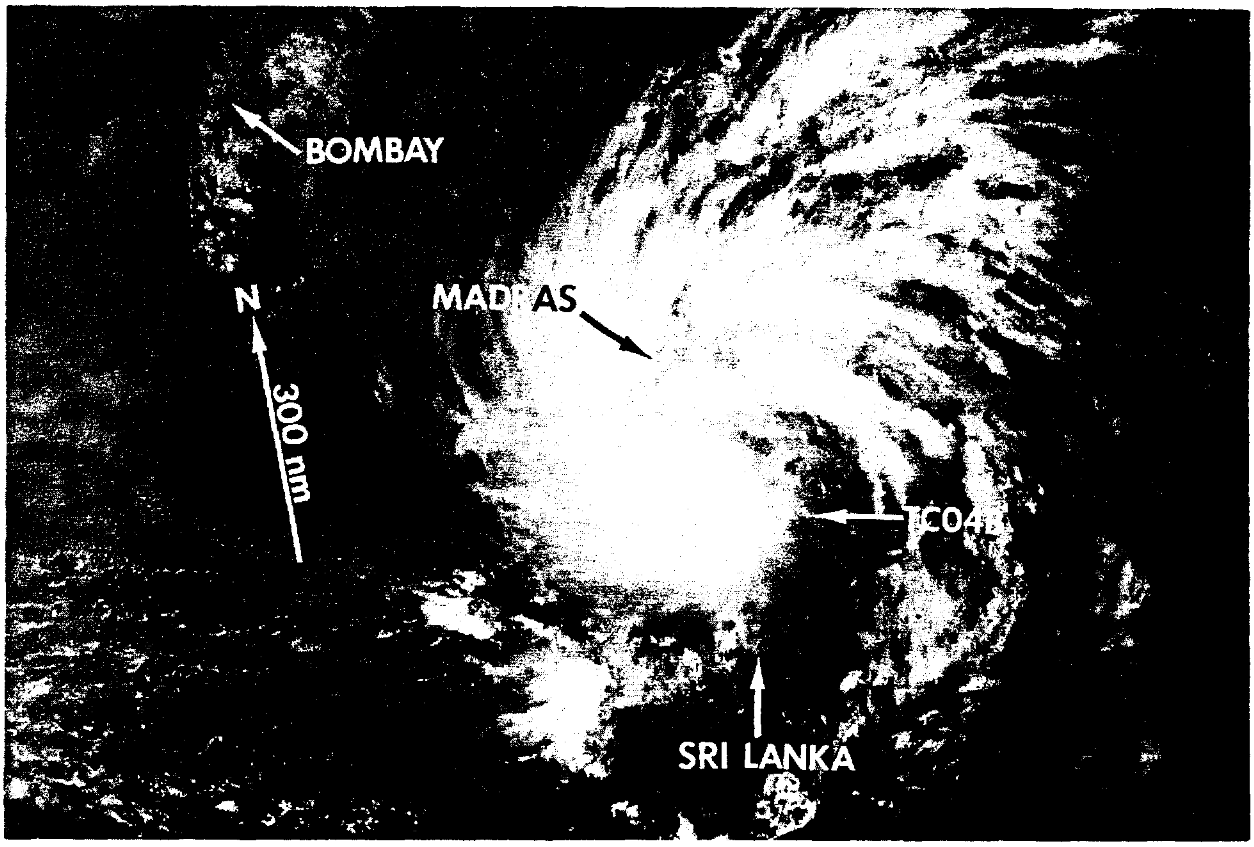


Figure 3-04B-1 Tropical Cyclone 04B makes landfall on the southern coast of India at maximum intensity (140305Z November DMSP visual imagery).

Tropical Cyclone 04B was the only cyclone to develop in the North Indian Ocean during the fall transition season. After being initially detected on 9 November, the disturbance was mentioned on the 1800Z Significant Tropical Weather Advisory. It tracked westward in the Bay of Bengal for the next three days without a significant increase in organization. At 131800Z, a Tropical Cyclone Formation Alert was issued when 131200Z synoptic data revealed a well-developed upper-level anticyclone had developed over the broad low-level circulation center. Twelve hours later, the first warning on Tropical Cyclone 04B indicated that while the system was rapidly approaching the southern coast of India, it was expected to maintain sufficient organization after crossing the Indian peninsula to allow it to reintensify in the Arabian Sea. For this reason, JTWC continued to issue warnings while the cyclone was over land. After reaching its maximum intensity of 40 kt (21 m/sec) just prior to landfall, the system crossed the Indian coast near Nagappattinam approximately 140 nm (260 km) south of Madras at 142300Z. It did not reintensify in the Arabian Sea, and the final warning was issued at 160000Z.

Intentionally left blank.